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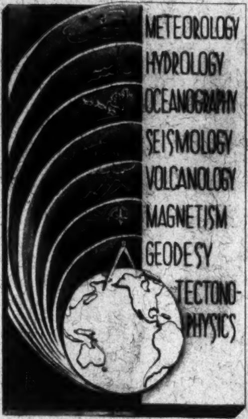
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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

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SHEAR PATTERNS OF THE EARTH'S CRUST

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Abstract--There is much evidence of the existence of a system of shear planes in the greatest part of the Earth's crust, and it seems likely that some planetary cause must have brought it about. Two possible causes are investigated here, (1) the decrease of the Earth's flattening because of the slowing down of its rotation by tidal friction and (2) a change of the axis of the flattening because of a movement of the Earth's rotation axis with regard to the crust. Only the latter phenomenon gives a good explanation of the existing system of shear planes. A good correlation is obtained with the Earth's topography, with the distribution of volcanoes, with the gravity fields in several areas, and with most of the evidence about shear planes brought out by the "lineament" tectonicians Hobbs, Sederholm, Daubrée, Sonder, and others.

The hypothesis is not in harmony with the continental drift theory of Wegener. At the end of the paper some tentative conclusions are drawn about the origin of the continents.

CHAPTER I

Introduction and Summary

In this paper we shall, in the first place, investigate the stresses in the Earth's crust which, because of the flattening, must be brought about by a shift of the polar axis with regard to the crust. In Chapter II we shall discuss what causes are most likely to lead to such a shift. We have two possibilities. In the first place we may suppose the crust to be a rigid shell around the Earth which may move with regard to the interior; in this way the polar axis will continually coincide with other points of the crust. We might suppose this movement to be brought about by subcrustal currents exerting a drag on the crust. In the second place the axis of rotation may shift with regard to the Earth as a whole. We might look for the cause of such a shift in the attraction by the Sun and the Moon. A theoretical treatment of this problem shows, however, that although through this cause the axis of rotation of the Earth is moving in space, its movement with regard to the Earth is insignificant [see "References" at end of paper, HELMERT, 1884]. So, as other outside forces are very unlikely, we may practically neglect this possibility for our purpose.

The writer has undertaken this investigation of the deformations of the crust caused by the shift of the polar axis because of the fact that the new method of echo-sounding, which allows a much more detailed sounding program than the old laborious methods, has revealed a more or less regular linear topographic pattern, mostly in two directions, over extensive parts of the ocean floors. This, for example, has been found in a great part of the North Atlantic, in the northwestern part of the Indian Ocean, in the North Pacific, in the Gulf of Aden, and elsewhere. Considering the great extension of most of these areas we cannot escape the suggestion of a planetary origin, and among the few possible suppositions of this kind a shift of the polar axis seems to be one of the most acceptable. As we shall show in Chapter III, we shall find that it fits the facts remarkably well. We shall also examine another supposition, namely, a variation of the flattening--a slowing down of the Earth's rotation, because of the tidal frictions, is not unlikely. We shall find, however, that the evidence does not agree so well with this supposition. In Chapter II, we shall also find theoretical grounds against it.

Our subject falls into three well-separated parts, dealt with in Chapters II to IV. In the first we shall deduce the crustal deformation and the stresses for the above two hypotheses, and we shall derive the pattern according to which we may expect the crust to give way. In the second we shall examine the topographical, geological, and geophysical evidence in order to see whether this points to any such phenomenon having occurred. As has already been mentioned, this evidence is in favor of a polar shift. In the third we shall study the way in which the deformation itself or the presence of the resulting fault planes in the crust may have led to the coming into being of topography correlated to the pattern of these planes. This study will involve a discussion of a few other crustal problems; this last part thus has a more or less speculative character.

To simplify our deduction of the deformations and the stresses of the crust in Chapter II, we shall assume the crust to be a complete rigid shell of the same thickness everywhere. We cannot make sure about this last assumption as we do not know the deeper crustal layers under the continents and the oceans and neither do we know the temperature at the base of the crust in either part. There is, however, no need to feel doubt about it because of the apparently contrary evidence given by gravity, namely, the great difference in thickness of the sial crust in the continents and the oceans as given by the Airy hypothesis on the isostatic balance. This balance depends on the depth of the discontinuities of density, while the thickness of the rigid crust is given by the depth of the limit of rigidity; there is no reason why this last depth should not be nearly constant over the Earth's surface. The large radius derived from gravity for the regional distribution of the isostatic compensation of volcanic islands is certainly in good keeping with the assumption that the rigid crust under the oceans is not thinner than under the continents. It has been found for the Hawaiian Archipelago, for Madeira, for the Bermudas, for St. Vincent (Cape Verde Islands), for Mauritius, and in a somewhat lesser degree for São Miguel and Fayal (Azores).

The problem we shall deal with in Chapter II thus reduces to the determination of the stresses originating in a shell of constant thickness when the shape of the shell changes. Considering the magnitude of the Earth's dimensions with regard to the thickness of the crust, it is clear that this shell cannot prevent the Earth from adopting the equilibrium shape belonging to the new conditions, that is, a changed position of the axis of rotation or a variation of the amount of the flattening. It is simple to derive in each of these cases how much the different parts of the shell have to move in the vertical sense to assume the new shape; the movements in the horizontal sense are not known beforehand.

For attacking the problem we shall begin by determining the equations between the stresses and the deformations of the crust for the general case of a change of shape, and, having obtained them, we shall apply them to our two cases, first to the case of a change in the amount of the flattening (as by its axial symmetry it is the simplest of the two) and then to the more complicated case of a shift of the polar axis.

By introducing in these formulas the figures for the elastical constants, we find that the stresses in case of a change of the flattening are probably not quite sufficient for explaining a crustal catastrophe, but for the case of a shift of the poles they may attain values of 2000 kg/cm^2 or more, and so it is not likely that the crust is able to stand them without giving way. The question then arises along which lines we may expect this to occur. According to the older hypothesis of Mohr this must take place in the planes of maximum shear; in each point there are two of these planes at right angles to each other. As, however, the two directions predominating in the topography of the North Atlantic and of the northwestern Indian Ocean clearly do not enclose right angles, there seems reason to apply the more modern theory of Bylaard and Van Iterson, according to which the angle between the two directions depends on the differences of the three principal stresses. Chapter II investigates this question, and we shall find it plausible that the shearing of the crust obeys Bylaard's formula. Applying it to our two cases of crustal deformation we shall derive the resulting net of shear over the Earth's surface for each of these cases. To do this we shall choose the data in such a way that in the North Atlantic the two directions are in harmony with the topography. For the case of polar shift this involves a movement of the pole from the neighborhood of Calcutta to its actual position before the shearing occurred; we thus obtain Net 1, as given in Chapter III. If the pole is assumed to have also shifted since the shearing, the range of the possible suppositions about the shift that has led to the shearing corresponding to Net 1 is wider. Assuming a shift of 10° at right angles to the original polar shift we obtain Net 2 (see Chapter III).

In case the flattening has changed we find a Net as shown in Figure 9 (see Chapter III). This can not be brought into good agreement with the directions of the topography in the North Atlantic unless it is assumed that since then the pole has moved from a point near Grant Land to the present position; in that case we obtain Net 3 (see Chapter III).

Chapter II also discusses the question of whether we may expect the fault planes of the shear net to be normal to the crust. For some parts of the Earth's surface this must be the case, but for other areas deviations are likely. The amount of the tilt is indicated in the three Nets.

At the end of the discussion concerning a shift of the poles an estimate is made of the forces required for such an event, and it appears that the forces causing tectonic orogeny, which are probably exerted by subcrustal currents, must have been amply sufficient. Even the slight forces resulting from the "Polfluchtkraft," which have lately been redetermined by H. Kuiper [1943], may have appreciably contributed to it, although they can not have brought it about completely.

Chapter III investigates and discusses the evidence at the Earth's surface which may shed light on the question whether a shift of the poles or a change of the flattening have indeed occurred. We have three sources of information available, namely, topography, geophysical evidence, and geology. These three sources are successively examined and compared with the three Nets. As the submarine topography is not subject to erosion, it may be expected to furnish a more reliable base for the investigation than the land topography and so the study of the topography is mainly restricted to the oceanic areas. To determine the correlation of the topography of the oceanic areas with the three Nets we have measured for each ocean, as far as it is sufficiently sounded, the lengths of the topographic features in harmony with the Nets inside deviations of 12° and compared their sums to the sum of the lengths agreeing in the same way to the directions of an arbitrary Net for which we have chosen the directions bisecting the angles of the Net 1. The results are given in Table 3. For all the oceans together, that is, for about one-half of the Earth's surface, the sum for Net 1 is 2.34 times that for an arbitrary net, while Nets 2 and 3 show less correlation. We shall see that this ratio strongly points to a real relation between the topography and Net 1--the chances that this is accidental are negligible. The correlation is clearly shown also by our map. As it concerns the topography of such a great part of the Earth's surface, the result carries much weight in favor of the hypothesis of a shift of the poles. As the other two Nets show less correlation, we shall henceforth disregard them.

The great number of topographic lines correlated with our Net provides a problem to be dealt with in Chapter III. The view is defended there that when the growing stresses during the polar shift brought about the first plastic deformation, a kind of hardening occurred--which in this case may perhaps, at least partially, have taken place by the sealing up of fault planes by magmatic intrusions--and thus a new fault plane must have been formed elsewhere. The manifold repetition of this process may have led in this way to the great number of fault planes indicated by the correlated topography. It seems possible that finally, in analogy to the breaking of a steel strip after many zones of flow have become inactive by hardening, shear of a greater amount has occurred in a limited number of these fault planes.

The map shows also a curious correlation with the trend of many continental coasts. We may notice this, for example, for the east coast of Asia, the north, west, south, and northeast coasts of Australia, the west coast of North America, the northwest, northeast, and east coasts of South America, and the northwest and east coasts of Africa. It further strikes us that at least part of the coasts that are not in harmony with the shearing net are situated in areas where the value of the shearing stress is small, and that we thus can understand their deviating from the directions of our Net. As this correlation is difficult to explain, a special investigation of it is made in Chapter III, and there, in the same way as mentioned above, a ratio of 1.56 is obtained. Although this is less than that obtained for the submarine topography in general, it seems likely that a real connection exists. The problems involved are discussed near the end of Chapter IV.

Examining the topographic lines in harmony with our Net, it is found that many of them appear to continue over great distances and from one topographic feature to another. This is found, for example, along the east coast of South America continuing along the northwest coast of Africa, along the east coast of Spain, and also the west coast of the Malay Peninsula and of Sumatra, which may be continued along the west coast of Australia. (Other instances are mentioned in Chapter III, where they are shown on the map of Figure 10.) They may be expected to represent zones in which considerable shearing occurred; in this case we can understand that they must continue over great distances. The differences of the topographic features in the same belt point to the fact that differences in level on both sides of the shearing plane must have been brought about by other phenomena taking place after the shearing.

The geophysical evidence is given by gravimetric surveys and by seismological results. The first mention is made in Chapter III of the East Indies, where the distribution of the anomalies of gravity shows a clear correlation with the directions of our Net. Besides, the gravity field suggests that the compression of the crust in this area mainly takes place in one direction--this also coincides with one of the directions in the Net. The topography of the Archipelago likewise shows a correlation. In the West Indies the correlation of the gravity field and of the topography to our Net is less, although several topographic features are in good harmony with it.

A remarkable instance of a gravity field showing a strong correlation to our Net is provided by the detailed anomaly map of the Netherlands obtained by recent surveys. Former maps of this area based on a less detailed gravity survey show this much less clearly; they do not reveal the sub-surface structures with sufficient distinctness. Another instance of a good correlation is given by the gravity field in the Western Mediterranean.

For the seismological evidence we shall mainly revert to Sieberg's well-known studies about the geographical distribution of centers of earthquakes, which he bases on the combination of the seismological data with what is known about the geological features. The great majority of the maps given by him in his "Erdbebengeographie" in Gutenberg's Handbuch der Geophysik [1932] are in good harmony with our Net and thus give a valuable support to our hypothesis.

In Chapter III a short summary is also given of Visser's study on the correlation with our Net of the Earth's magnetism. It gives a curious result which merits further investigation.

The writer, not being a geologist, does not attempt to investigate and discuss the geological evidence touching the question whether a world-wide net of fault planes corresponding to the hypothesis is present in the crust; he must leave this difficult subject to geologists. Brief mention is made, however, in Chapter III of the many data collected by geologists Daubrée, Hobbs, Sederholm, Sonder, and other "lineament" tectonicians, who have long suspected such a net to exist, mainly because of geological, geomorphological, and topographical indications on the continents. Nearly all of this material supports our hypothesis, and, as it was obtained and published quite independently and long ago, this support carries much weight; the writer had no knowledge of its existence when he elaborated his hypothesis. The data mainly concern Africa, where Krenkel's well-known map shows lines in remarkable harmony with our map, and Europe, where many authors have contributed in collecting evidence and where also the topography of the Variscian and Alpine orogeny shows much correlation; data for North and South America and for Asia are also present. (For further details refer to Chapter III.)

Admitting that the combination of facts and correlations from all the sources mentioned is not likely to be accidental, another explanation than that of a polar shift seems improbable, because another phenomenon could hardly have brought about the same shearing net and the relations defined by complicated mathematical formulas. If our hypothesis is adopted, the question arises at what date did it occur. It seems likely that it occurred in one of the early periods of the history of the Earth's crust, probably long before the Cambrian, as it is difficult to account for the continental coasts having adopted their present general trends in any more recent period. If the correlation of the coasts is regarded as accidental, which does not seem likely, the answer to our question becomes more vague. In view of the correlation to the lines of Variscian orogeny, however, the date may be at least pre-Carboniferous and probably earlier.

It must be realized that many of the shear planes must have been maintained throughout great parts, or perhaps the whole, of the crustal history; in all cases where forces have since worked on the crust, the chances must have been great of differential movements of the separate crustal blocks and, therefore, of new shearing along these planes. If the crust had been covered by more recent sediments, these layers must have had insufficient strength for resisting the movements, and so the shear planes must have penetrated these layers also. It may, therefore, be expected that a continuous rejuvenation of the Net has taken place at the Earth's surface. Doubtless this must have been one of the main causes of the volcanicity of the alkaline type.

A second question arises concerning the causes of the supposed shift of the poles; this point has been touched on in Chapter II. The early date at which we must expect the event to have happened makes it impossible to give any definite answer, but we may, of course, attempt a speculation about it. Basing it on the hypothesis that the orogeny during the tectonically active periods of the crust's history has been caused by subcrustal currents--probably convection currents brought about by the Earth's cooling--it seems plausible that these currents, by exerting forces on the crust that are not in equilibrium, have been the cause of the rotation of the crust and, therefore, of the shift of the poles, in one of the first of these periods. It further appears possible that the shearing of the crust resulting from this event has put an end to this possibility of rotation of the whole crust because of the great amount of energy absorbed by the relative movements of the separate crustal blocks on which, henceforth, the subcrustal currents exerted their forces. Shifts of the pole of great extent would thus be excluded, and this would explain the fact that the present position of the pole still more or less coincides with the meridian along which the pole wandered before the catastrophe occurred. If great movements had since taken place, this coincidence would have to be considered as purely accidental, and, although there is no objection to doing so, the other viewpoint seems more satisfactory.

Chapter III finishes with a few general conclusions which may be drawn from our hypothesis. We may affirm that since the movement of the poles has led to the shearing of the crust, no continental shift of any appreciable amount can have occurred, because such a movement would have disturbed the Net. Moreover, the shearing of the crust can only have taken place in the manner described if the crust formed a rigid whole, and this excludes the idea of any continental shift of large dimensions. We need not stress the importance of this conclusion for geophysics, especially for the hypothesis of Wegener, which it forces us to abandon.

We may further state that the remarkable correlation of the shearing net with the topography of the Earth's surface provides us with a striking confirmation of the validity of Bylaard's hypothesis for the shearing phenomena in the Earth's crust. Bylaard himself has already affirmed and discussed this validity in papers concerning the crustal processes in the East Indies [BYLAARD, 1936, 1935].

We may remark, finally, that our hypothesis is based on the simple mechanical picture of a rigid crust floating on a plastic substratum and forming a closed shell around the Earth. This picture has already proved its value in several cases, for example, for the explanation of isostasy as given by Airy, for the adaptation of this explanation to regional isostatic compensation [VENING MEINESZ, 1939, 1941 a], and for the hypothesis of crustal buckling made to explain the belts of strong negative gravitational anomalies in the East and West Indies [see Chapter IV]. Although this picture is obviously too simple, because other processes must have played a part in the history of the Earth's crust as, for example, metamorphism, chemical processes, and differentiation, it in the main, nevertheless, covers the behavior of the crust sufficiently to explain most of its major phenomena. The present investigation seems again to confirm this viewpoint.

In Chapter IV the question of how the shearing of the crust can have brought about the correlated topography is discussed. In the first place the shearing itself must have caused ridges or troughs because of the fact that in general the plastic deformation in these zones must have involved displacements which at the surface had a vertical component. We shall, however, see that the amount of the rising or sinking must have been small, and, as it occurred so long ago, it seems doubtful whether even in the submarine topography, where no erosion has worked, traces of these features can still be present.

The second cause, the volcanicity, to which the shearing has no doubt given rise, must have had a much more important effect. It is sure to have continued up to the present time; the rejuvenation of the shearing in the fault planes caused by other forces working on the crust, as already remarked, must have reopened numerous passages to the magma. We have several indications that much of the submarine relief in the oceans has indeed this origin. In the first place most of the islands are volcanic, in the second place the linear character of the majority of the ridges points this way, and in the third place the irregular length profile and the variable breadth of these ridges thus find their simplest explanation. On the other hand, these arguments give a confirmation to our supposition that this oceanic topography is connected with shear planes in the crust.

Further confirmation of our hypothesis is given by the fact that the volcanicity of the alkaline type at the Earth's surface is practically confined to the areas where the critical stress caused by the polar shift has been large, that is, more than three-quarters of its maximum value. As the map shows, a remarkable instance of this is given by Iceland, which is situated on a narrow ridge of high stresses. This question is further examined in Chapter IV, in which mention is made of the fact that the gravity results hitherto obtained in the oceans are in harmony with our picture.

Besides the volcanic origin there are other ways in which we may imagine the presence of fault planes in the crust to have led to the initiation of correlated topography; these are successively dealt with in Chapter IV. In the first place, unevennesses of the planes may cause matter to be squeezed out during the shearing movements along these planes. Secondly, tilted fault planes, combined with tension or compression in the crust, must bring about topography; TABER [1927] first drew attention to this. These topographic features may take the shape of escarpments, "Graben," or "Horsts." Thirdly, epeirogenetic causes giving different vertical movements to the crustal blocks on both sides of a fault plane must also cause an escarpment along the line of this plane. In the fourth place, erosion of the fluvial, as well as of the glacial, type must bring out the presence of a fault plane; SONDER [1938] has dealt with this subject at some length, and so we may refer to this publication for details.

From study of the effect of tectonic action, we may expect that the presence of fault planes must have affected strongly the results of tectonic forces working on the crust. Adopting the hypothesis that in the area of the principal folding and overthrusting, the crustal shortening brings about a downward buckling process of the crust, we shall find that a shear plane, which also involves a zone in which plastic deformation has taken place, must lessen the force needed for this buckling, and so this last process will follow, by preference, the course of the plane. But, besides, the subcrustal currents probably responsible for the tectonic forces working in the crust must give, in many cases, different movements to the separate crustal blocks, and so shearing will occur in the fault planes between the blocks. As this must give rise, in general, to topography over these planes because of the effects already enumerated, we may expect that the orogenic belt shows other topographic ridges correlated with our Net of fault planes besides that caused by the main crustal shortening. We thus can understand a great part, if not all, of the complicated pattern of the tectonic trends in these belts. Examples given by the Alpine and southern Asiatic areas and by the East Indies and the Philippines are cited in Chapter IV. In the first area we recognize the directions of the Apennines, the Dalmation mountain ranges, the greatest part of the Carpathians, and part of the Alps themselves as belonging to our Net; in the second area the mountain ranges of Baluchistan and Burma seem to be correlated; and in the last area the part played by the fault zones of the west coast of Sumatra and of the eastern border of the Philippines may explain the origination of the great orogenic arc. There can be no doubt that the conception of a subcrustal current acting on a system of crustal blocks separated by fault planes may give a simpler explanation of the intricate pattern of tectonic orogeny than the supposition that forces have worked on an unbroken crust; in the last case the assumptions about these forces cannot be otherwise than complicated. The understanding thus obtained of these difficult problems seems to constitute a valuable point in favor of our hypothesis.

In the last place we shall attack the hardest problem of all, the explanation of the correlation of the edges of continental shelves with our Net. This introduces the following difficulty: It is well known that the seismic evidence is in favor of the granite layer of the crust being thicker in the continents than in the oceans; in part of the Pacific, and perhaps in the Arctic, this layer appears even to be entirely absent. According to the gravity results obtained in coastal profiles, this transition in thickness, in general, is rather sudden, and it coincides, or nearly coincides, with the edge of the shelf. On the other hand, it is clear that the shearing of the crust can not have affected its constitution and so this can not in itself have brought about the difference of the thickness of the granite layer. So we are bound to assume that these differences, at least for the correlated shelf edges, came into being after the shearing had taken place. The problem is how this can have taken place. In examining this problem we shall see that practically the only possible solution is given by the supposition that the course of a great part, if not all of the continental edges, is of a more recent date than the granite blocks of the continents themselves and that thus their formation can be posterior to the shearing catastrophe and can be correlated to its net of lines. This is immediately clear for those shelf edges where the trend is determined by recent orogeny, as, for example, is the case for the west coast of North and South America and the east coast of Asia. Considering the probability mentioned above that tectonic deformations have a preference to follow fault zones, it is clear that our problem is solved for these coasts; we need not be surprised to find that their trend shows a correlation to our Net. The figure for this correlation is mentioned on page 38; it is about the same as that for all the coasts taken together. From this result we can suppose that the directions of at least the majority of the other coasts have been determined likewise by orogeny, but that this has occurred in pre-Cambrian periods of such early date that this origin can no longer be traced by geological means. It is clear that thus our problem would be solved. In treating this hypothesis in Chapter IV we shall add a discussion of its compatibility with two recent suppositions about the origin of the continents, namely, those of Umbgrove and the writer, We shall find that this does not present difficulties but that we can not derive our hypothesis directly from one of them.

Concluding, we may say that the correlation of the continental edges with the shearing net can be explained by assuming that these edges, at least partially, have been brought about by tectonic phenomena. A little new light is thus shed on the problem of the origin of the continents.

CHAPTER II

The Stresses and Deformations of the Crust Caused by a Shift of the Poles or by a Change in the Flattening

As already mentioned in Chapter I, we shall investigate here the stresses and deformations which, because of the flattening, will occur in the Earth's crust when the polar axis changes its position with regard to the crust. Besides this main problem we shall also study the effect on the crust of a change of the flattening.

Before taking up these subjects we shall briefly discuss the possibility of one of these phenomena taking place. A shift of the axis of rotation with regard to the Earth as a whole does not seem likely. It is obvious that it could only be brought about by external forces, and in this regard there are practically present only the attractions exerted by the Sun and the Moon. It is true that these forces, because of the flattening, or to be more exact because of the difference of the moments of inertia around the axis of rotation and around an axis in the equator, affect the rotation of the Earth, but the study of this effect [HELMERT, 1884] has shown that only the change of position of the axis of rotation in space is important; the disturbance of the axis with regard to the Earth is small and quite negligible for our subject.

The second possibility of a shift of the poles with regard to the crust, namely, by a gliding of the crust over the Earth's interior, seems more acceptable. There is no doubt that the deeper layers are plastic and that they allow movements under small differences of stress; otherwise the isostatic balance could not be maintained so well. There is no objection, therefore, in assuming the presence of subcrustal currents, possibly caused by some kind of convection brought about by the inward temperature gradient. Such assumed currents may explain tectonic forces in the crust, which otherwise are difficult to account for. This subject is further discussed in Chapter IV. The system of these currents must exert a drag on the crust, which, if we consider the crust as a rigid whole, will have a resultant momentum tending to rotate the crustal shell around the interior.

Besides this possible cause there is another to be mentioned, namely, the "Polfluchtkraft." The momentum resulting from these forces, however, is small, and, according to a recent investigation made by H. KUIPER [1943], it is questionable, although just possible, that it is in itself sufficient to cause large shifts of the poles; it may have contributed to the movement needed for our hypothesis. We shall find hereafter that this last movement must have taken place along the meridian of 90° east of Greenwich and that the middle of the start and the finish must be situated at latitude 55° north. As Kuiper found [see also MILANKOVITCH, 1938] that the maximum orbit which the "Polfluchtkraft" may possibly have brought about begins at 59°.2 north and 72°.7 east, we see that it does not deviate much from the second part of the orbit required for our hypothesis. As the "Polfluchtkraft," however, is caused by the present configuration of the continents and the oceans, it is possible that it contributed to the shift of the poles if this movement occurred later than the formation of the continents, and we have already mentioned in Chapter I that the correlation of the net of deformation to the continental coast lines rather points in the opposite sense. It still remains possible, however, that at the time of the polar shift other topographic features were present and that the corresponding Polfluchtkraft contributed to the shift; it may even have caused it entirely.

We shall now consider the possibility of a change of the flattening. There can be no doubt that such a change must have occurred; the tidal friction is sure to have slowed down the Earth's rotation, and this must have affected the flattening. Besides, possible changes of the Earth's diameter or shifts of its masses must likewise have had an effect, but it is clear that since the solidification of the Earth's crust this can not have been important.

JEFFREYS [1929, Chapter IV] deals at length with the subject of tidal friction. He derives the slowing down of the Earth's rotation from the secular acceleration of the Sun and the Moon, and the result given by him is that 1600 million years ago the period of rotation must have been 0.84 of the present day. This corresponds to a flattening of 1/210. Still longer ago the tidal friction must have been greater, because the Moon was nearer the Earth, and shortly after the formation of the Moon by the disruption of the Earth the day must have been about five hours and the flattening 1/13.

It is difficult to estimate at what date the crust formed a closed shell firm enough to develop stresses of a more or less permanent character when adjusting its shape to the change of the flattening. If this occurred about 1600 million years ago we shall find in this Chapter that the change of the flattening since that time is not quite sufficient to explain the shearing of the Earth's crust, even if we put its date in a recent period. JEFFREYS [1929] in his discussion of the effect of a change of rotation on the Earth's surface features, however, reckons with the possibility that the tidal friction in the earlier part of this period was greater than the computed amount and in that case the shearing of the crust may have been possible. This, moreover, is certainly the case if we put the formation of the crustal shell at an earlier date, and so we may conclude that the shearing of the crust by this cause, even at an early period of the crust's history, is not out of the question.

We may now speculate on the question of which of the two phenomena--a shift of the poles or a change of the flattening--is the most likely to have caused a disruption of the crust. Admitting the possibility of both, the fact that the stresses in the first case must have originated so much more quickly than in the second seems to be in favor of the first supposition. Assuming that the shift of the poles was caused by subcrustal currents, we may suppose this to have come about during part of a period of great tectonic activity in the crust. Taking the mean of the figures of eleven of these periods given by KUENEN [KUENEN, 1941, UMBGROVE, 1942], we find 55 million years, while the mean duration of the ten dormant periods is 120 million years. So we may expect stresses leading to the shearing of the crust to develop in a period of some 50 million years or less. For a shift of the poles over 70°, as mentioned in Chapter I, this corresponds to a velocity of the movement of about 16 cm per year, and this order of magnitude is in good agreement with the values of 19 cm and 14 cm found by LAMBERT [1922] and by WANACH [1927] for the present velocity of the polar movement. It is likely that in earlier periods of the Earth's history, when the viscosity of the subcrustal layers must have been less, the speed was even greater.

Stresses brought about by the change of the flattening must be expected to require a much longer period before they can give rise to a shearing of the crust; according to what has been said this must probably have taken at least 500 to 1000 million years. This long duration must increase the chances that the relaxation of the stresses prevents them building up to the critical value. So this argument is favorable to the first supposition. As already mentioned in Chapter I this result is in harmony with the evidence given by the topographical and geological features of the Earth's surface.

This evidence gives a slight indication that the movements of the poles have been on a smaller scale since the crustal shearing. It is easy to find a plausible cause for this. We may expect that once the crust has been broken up in separate blocks, the energy provided by eventual subcrustal currents must partly be absorbed by friction between these blocks and that less is available, therefore, for the rotation of the crust as a whole.

In this connection another speculation is, perhaps, worth-while. It might be considered likely that only since the breaking of the crust in separate blocks could great folding come into being in orogenic areas; great compressive movements in more or less limited areas may be better understood when the disruption of the crust makes possible relative movements of these blocks. This condition of the crust may explain also the complicated pattern of the tectonic axis in these areas; in most cases more than one block must have moved and the working of the shear planes must have contributed to this pattern. Lastly it is well conceivable that the crust, as long as it formed an unbroken shell, was able to resist the tectonic stresses working on it.

Taking up the main problem of the stresses and deformations of the crust caused by a shift of the poles or a change of the flattening, we shall assume the crust to have a uniform thickness over its whole surface. It is difficult to be sure about this supposition. We do not know much about the deeper layers, their physical properties, and the temperatures, so an exact treatment of the matter is out of the question. We can say, however, that the lower boundary of the rigid crust need not coincide with one of the discontinuity surfaces of density and so the data given by gravity about the depths of these surfaces have no bearing on our problem. We need not be influenced, therefore, by the fact that, according to Airy's hypothesis about isostasy, the thickness of the sialic layer must be greater in the continents than in the oceans. The results of the determinations of gravity over, and in the neighborhood of, volcanic islands show, on the contrary, that the rigid crust can not be thinner there than over the continents; the radius of the regional distribution of the isostatic compensation best fitting the gravity results in these areas is not smaller than for continental areas, and so the bending properties of the oceanic crust point to a thickness at least as great as for the continents [VENING MEINESZ, 1941 b].

Besides assuming the crust to have uniform thickness, we shall also suppose it to behave as a homogeneous, isotropic elastic body and so neglect possible differences in elastic properties. There is no doubt that such differences must be present, and so we may expect that on this account deviations from our deductions will occur.

Our problem thus is to derive the stresses and deformations in a homogeneous crustal shell of uniform thickness when it changes its shape under the effect of a shift of the poles or of a change of the flattening. Each of these phenomena causes the elements of the crustal shell to undergo small translations of which the component s_ρ normal to the crust changes the initial shape of the shell into its final figure. As the crust is obviously too weak to prevent the Earth from adopting the equilibrium figure, we can determine the shift between both figures and so consider s_ρ as given. It further is simple to see that if in our result we neglect the order of the flattening, we may assume the initial shape to be spherical. Lastly we can show that, as for both phenomena, s_ρ is only slowly variable over the Earth's surface, the bending stresses in the crust may be neglected--we shall presently return to this point and shall see that this is indeed allowable.

Starting from these assumptions, we shall now derive the equations for the stresses and deformations of a rigid spherical shell of uniform thickness of which the elements are subjected to small translations s_ρ normal to the sphere. We shall begin by leaving s_ρ undefined, substituting afterwards the values for the two cases to be investigated--the shift of the poles or the change of the flattening. Let R denote the Earth's radius, T the thickness of the crust, δ and α polar coordinates with regard to an arbitrary coordinate axis through the Earth's center, δ being the angle between this axis and the radius of the crustal element under consideration and α the angle of the plane through this radius and the axis and an arbitrary zero plane through the axis which we shall choose through the axis of rotation of the Earth, σ_δ and σ_α the normal components of the stresses working in cross sections of the crust corresponding to these coordinates, τ the shearing component of these stresses parallel to the crust, and σ_ρ the normal component of the stresses in planes parallel to the crust. We shall give positive sign to τ if, as in Figure 1, the direction of the force working in planes through the coordinate axis and acting on the crustal element at the side of increasing α is away from the axis. σ_δ, σ_α, and σ_ρ do not include the part of the stresses resulting from the hydrostatic pressure in the crust which may be assumed to have always been present; as we shall afterwards discuss, we may suppose that it has played no part in the deformations of the crust we are investigating. The assumption that the bending stresses may be neglected implies that the stresses σ_δ, σ_α, and τ are constant over the whole thickness of the crust and that the other shearing components of the stresses are zero. We likewise find that σ_ρ increases linearly with depth from a value of zero at the surface to the value, σ_r, it has at the lower boundary of the crust.

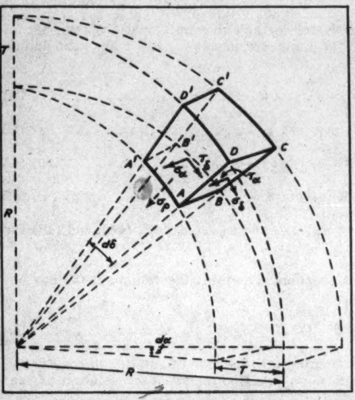


Fig. 1--Forces acting on element of spherical shell

For an elemental prism, ABCDD'A'B'C', extending over the full thickness of the crust and bounded by two planes through the coordinate axis enclosing an angle $d\alpha$ and two conic surfaces described around the axis with angles differing $d\delta$, we find the following conditions of equilibrium:

In the direction AA', $\sigma_\alpha TR \cos\delta d\delta d\alpha - (\partial\sigma_\delta/\partial\delta)TR \sin\delta d\delta d\alpha - \sigma_\delta TR \cos\delta d\delta d\alpha + (\partial\tau/\partial\alpha)TR d\delta d\alpha = 0$

In the direction AB, $(\partial\sigma_\alpha/d\alpha)TR d\delta d\alpha - (\partial\tau/\partial\delta)TR \sin\delta d\delta d\alpha - \tau TR \cos\delta d\delta d\alpha - \tau TR \cos\delta d\delta d\alpha = 0$

In the direction AD, $\sigma_r R^2 \sin\delta d\delta d\alpha + \sigma_\delta TR \sin\delta d\delta d\alpha + \sigma_\alpha TR \sin\delta d\delta d\alpha = 0$

The third terms of the first two equations are brought about by the difference in size of the surfaces ABCD and A'B'C'D'. By simplifying the three equations we derive equations (1A), (1B), and (1C).

$$(\sigma_\alpha - \sigma_\delta)\cos\delta - (\partial\sigma_\delta/\partial\delta)\sin\delta + (\partial\tau/\partial\alpha) = 0 \quad \ldots\ldots\ldots\ldots \text{(1A)}$$

$$(\partial\sigma_\alpha/\partial\alpha) - (\partial\tau/\partial\delta)\sin\delta - 2\tau\cos\delta = 0 \quad \ldots\ldots\ldots\ldots \text{(1B)}$$

$$\sigma_r + (T/R)(\sigma_\delta + \sigma_\alpha) = 0 \text{ and } \sigma_r = -(T/R)(\sigma_\delta - \sigma_\alpha) \quad \ldots\ldots\ldots\ldots \text{(1C)}$$

By applying the last formula to a layer of the crust between the surface and a depth z, we may write it $\sigma_\rho = -(z/R)(\sigma_\delta + \sigma_\alpha)$, and so we see that if σ_δ and σ_α are constant over the whole thickness of the crust, σ_ρ must indeed increase linearly with the depth z as we mentioned above.

We may likewise conclude from (1C) that σ_r is small with respect to σ_δ and σ_α; as the ratio (T/R) is less than one per cent, we may say the same of the ratio $[\sigma_r/(\sigma_\delta + \sigma_\alpha)]$. As we have already neglected quantities of the order of the flattening we may, therefore, do the same for σ_r with regard to σ_δ and σ_α.

To express the relations of the stresses and the deformations we shall introduce the translations s of the elements of the crust and its components s_δ in the direction of the great circle through the origin of the polar coordinates, s_ρ in the sense of the Earth's radius and s_α perpendicular to s_δ and s_ρ. We shall give positive sign to s_ρ if it is directed outwards and to s_δ and s_α if their directions coincide with increasing δ and α.

Neglecting σ_ρ and σ_r and introducing Young's modulus E, the shear modulus G and Poisson's coefficient m we find

$$[\sigma_\delta - (1/m)\sigma_\alpha]/E = (1/R)(\partial s_\delta/\partial\delta) + (s_\rho/R)$$

$$[\sigma_\alpha - (1/m)\sigma_\delta]/E = (s_\delta/R)\cot\delta + (1/R)(\partial s_\alpha/\partial\alpha)\operatorname{cosec}\delta + (s_\rho/R)$$

$$(\tau/G) = (1/R)[-(\partial s_\delta/\partial\alpha)\operatorname{cosec}\delta - (\partial s_\alpha/\partial\delta) + s_\alpha\cot\delta]$$

From these equations we obtain

$$\sigma_\delta - (1/m)\sigma_\alpha = (E/R)[(\partial s_\delta/\partial\delta) + s\rho] \tag{2A}$$

$$\sigma_\alpha - (1/m)\,\sigma_\delta = (E/R)[s_\delta\cot\delta + (\partial s_\alpha/\partial\alpha)\operatorname{cosec}\delta + s_\rho] \tag{2B}$$

$$\tau = [mE/2(m+1)R][-(\partial s_\delta/\partial\alpha)\operatorname{cosec}\delta - (\partial s_\alpha/\partial\delta) + s_\alpha\cot\delta] \tag{2C}$$

In these equations s_ρ is given by the data of the problem. For determining the five unknown quantities σ_δ, σ_α, τ, s_δ, and s_α we dispose of the five equations (1A), (1B), (2A), (2B), and (2C) and after doing this can derive σ_r from (1C).

The solution of these equations becomes much easier for an axisymmetrical problem, as, for example, the case of a change of the flattening. In these circumstances s_α and τ are zero and the equations (1) and (2) reduce to

$$(\partial\sigma_\delta/\partial\delta) = (\sigma_\alpha - \sigma_\delta)\cot\delta \tag{3A}$$

$$\sigma_r = -(T/R)(\sigma_\alpha + \sigma_\delta) \tag{3B}$$

$$\sigma_\delta - (1/m)\sigma_\alpha = (E/R)[(\partial s_\delta/\partial\delta) + s_\rho] \tag{4A}$$

$$\sigma_\alpha - (1/m)\sigma_\delta = (E/R)(s_\delta\cot\delta + s_\rho) \tag{4B}$$

Introducing the given value of s_ρ we can derive σ_δ, σ_α, and s_δ from (3A), (4A), and (4B) and afterwards σ_r from (3B).

Assuming that the flattening β diminishes by an amount Δ and that the volume of the Earth remains the same we have (5A) for s_ρ.

$$s_\rho = \Delta R[\cos^2\delta - (1/3)] \tag{5A}$$

In this case the coordinate axis has been chosen coinciding with the axis of rotation of the Earth and so δ is the colatitude. By means of this formula for s_ρ we find the following solution of the equations (3) and (4).

$$s_\delta = -[2(m+1)/(5m+1)]\Delta R\sin\delta\cos\delta \tag{5B}$$

$$\sigma_\delta = [m/(5m+1)]\Delta E[\cos^2\delta + (1/3)] \tag{5C}$$

$$\sigma_\alpha = [m/(5m+1)]\Delta E[3\cos^2\delta - (5/3)] \tag{5D}$$

$$\sigma_r = -[4m/(5m+1)]\Delta(T/R)E[\cos^2\delta - (1/3)] \tag{5E}$$

For computing the stresses by means of these formulas we have to introduce values for the elastic constants E and m. According to GUTENBERG [1939] the bulk modulus k for the granitic layer is about 500,000 kg/cm^2 and for deeper crustal layers it is probably not far from 1,000,000 kg/cm^2. Considering these figures we shall adopt a mean value of 650,000 kg/cm^2 for the whole crust. For Poisson's coefficient m GUTENBERG [p. 358, 1939] gives slightly more than four for the granitic layer and four for the deeper continental layers, and so we shall probably be not far from the mark if we introduce a value of 4.1 for the whole crust. As we have $E = [3(m-2)/m]k$, we obtain from these figures a value of E of 1,000,000 kg/cm^2.

We shall further introduce R = 6371.2 km and a thickness T of the rigid crust of 30 km. This last value is in good agreement with the radius of the regional distribution of the isostatic compensation as derived from gravity results. This radius is given by the formula with

$$r = 2.905\,\ell \quad \ldots\ldots\ldots\ldots \quad \text{(6A)}$$

$$\ell = \sqrt[4]{m^2ET^3/[12(m-1)(\Theta_1 - \Theta_0)g]} \quad \ldots\ldots\ldots\ldots \quad \text{(6B)}$$

and introducing the above values for E and m and putting the difference of the surface density Θ_0 and the subcrustal density Θ_1 at 0.6 we obtain $\ell = 80$ km. This value is in harmony with the value derived from many gravity data, as, for example, those found for Hawaii and Madeira [VENING MEINESZ, 1941 b]. The value for T, moreover, only enters in the result for σ_r; it is interesting to notice that it does not affect the values of the main stresses σ_δ and σ_α.

We have lastly to decide on the value we shall introduce for the change of the flattening, Δ. At present the flattening is 1/297 and as we have mentioned, Jeffreys determined it for 1600 million years ago at 1/210; we, therefore, shall put Δ at $[(1/210) - (1/297)] = 0.00140$.

By means of these values we shall compute the stresses and deformations given by the formulas (5). We obtain for the poles values as in (7).

$$\left.\begin{aligned} \sigma_\delta &= \sigma_\alpha = [4m/3(5m+1)]\Delta E = 356 \text{ kg/cm}^2 \\ \sigma_r &= -[8m/3(5m+1)]\Delta(T/R)E = 3.4 \text{ kg/cm}^2 \\ s_\rho &= (2/3)\Delta R = 5.9 \text{ km} \\ s_\delta &= 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (7)$$

The values of about 360 kg/cm^2 found for σ_δ and σ_α represent the maximum values of the tensional stresses occurring over the Earth's surface and we find here likewise the maximum rise of the crust, namely, 5.9 km. The value of σ_r confirms our conclusion that the stress exerted by the substratum on the crust is negligible with regard to the stresses in the crust.

For the equator we obtain

$$\left.\begin{aligned} \sigma_\delta &= [m/3(5m+1)]\Delta E = 89 \text{ kg/cm}^2 \\ \sigma_\alpha &= -[5m/3(5m+1)]\Delta E = -\ 445 \text{ kg/cm}^2 \\ \sigma_r &= [4m/3(5m+1)]\Delta(T/R)E = 1.7 \text{ kg/cm}^2 \\ s_\rho &= -(1/3)\Delta R = -\ 3.0 \text{ km} \\ s_\delta &= 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad \text{(8A)}$$

The value of σ_α of about 450 kg/cm^2 is the maximum compression which occurs, and we have here also the maximum downward movement of the crust, namely, 3.0 km. This corresponds to a shortening of the equator of about 20 km and so this might have contributed to the shortening of the crust in the folded mountain ranges of north-south direction; the amount has originated, however, in a very long period, and so the contribution to each orogenetic period can not have been great. If, moreover, the hypothesis is true that the crust, at a very early stage of its history, was divided in blocks by a shearing process brought about by a shift of the poles, the above shortening of the equator must probably have taken place by an adjustment of the blocks along the shearing planes, and a contribution to the folding orogeny seems unlikely.

At the equator the difference of the stresses σ_δ and σ_α is maximum and, therefore, the shearing stress τ' likewise. We thus find this maximum value of the shearing stress to be

$$\tau'_m = [m/(5m+1)]\Delta E = 267 \text{ kg/cm}^2 \quad \ldots\ldots\ldots\ldots \quad \text{(8B)}$$

For the poles τ' is zero.

For latitude 45° we find

$$\left.\begin{aligned} \sigma_\delta &= [5m/6(5m+1)]\Delta E = 222 \text{ kg/cm}^2 \\ \sigma_\alpha &= -[m/6(5m+1)]\Delta E = -\ 44 \text{ kg/cm}^2 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots \quad (9)$$

$$\left.\begin{aligned} \sigma_r &= -[2m/3(5m+1)]\Delta(T/R)E = -0.8\ \mathrm{kg/cm^2} \\ s_\rho &= (1/6)\Delta R = 1.5\ \mathrm{km} \\ s_\delta &= -[(m+1)/(5m+1)]\Delta R = -2.1\ \mathrm{km} \end{aligned}\right\}\ \ldots\ldots\ (9,\ \text{conc.})$$

At this latitude the northward shift of the crust is maximum, namely, 2.1 km. The stresses and the vertical movement s_ρ are the mean here of the values at the pole and at the equator.

Examining the stresses we find, as mentioned already in Chapter I, that they are not quite sufficient in themselves to bring about a disruption of the crust; it does not seem likely that it has given way under this strain. It is, however, possible that the change of the flattening has been greater than the value we have introduced. In the first place, the tidal friction may have been stronger in the past, and in the second place, the crust may have solidified at a still earlier date and the flattening at that date must have differed more from the present value.

We have not yet investigated the way in which we may expect the crust, in case of a greater change of the flattening, to give way. We shall take up this subject at the end of this Chapter after first studying our main problem--the effect of a shift of the poles.

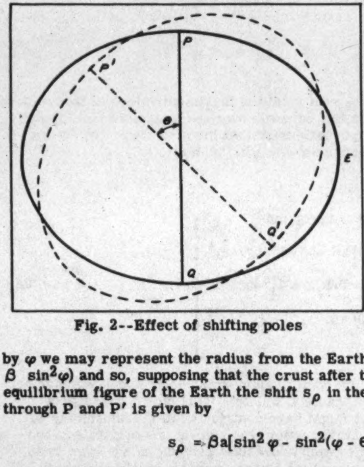


Fig. 2--Effect of shifting poles

For deriving the stresses and deformations caused by a shift of the poles we require the formula for the distance s_ρ of the crust's surface before and after the event. We assume that because of the movement of the crust around the Earth the pole after the movement coincides with the point P′ (see Fig. 2) at a distance θ from its initial position P in the crust, the angle θ being counted anti-clockwise in the Figure. The orbit described between P and P′ does not affect the following considerations; it may have been the meridian connecting both points and in this case the crust has rotated clockwise around an axis in the equator over the angle θ but it may also have been another orbit, for example, a rotation around an axis in an inclined position with regard to the plane of the equator.

Neglecting quantities of the order of the square of the flattening and denoting the latitude by φ we may represent the radius from the Earth's center to a point at the surface by $r = a(1 - \beta \sin^2\varphi)$ and so, supposing that the crust after the movement has adjusted itself entirely to the equilibrium figure of the Earth the shift s_ρ in the sense of the radius for points of the meridian through P and P′ is given by

$$s_\rho = \beta a[\sin^2\varphi - \sin^2(\varphi - \theta)] = \beta a \sin\theta \sin(2\varphi - \theta) \ldots\ldots\ldots\ldots (10)$$

This displacement s_ρ has its maximum value $\beta a \sin\theta$ for $\varphi = (45^\circ + \theta/2)$ and its largest negative value $-\beta a \sin\theta$ for $\varphi = (-45^\circ + \theta/2)$.

It is simple to prove that this deformation of the crust can be obtained by the superposition of two deformations of the kind given by (5A), namely, one with the axis coinciding with the direction $\varphi = (45^\circ + \theta/2)$ for which $\Delta R = \beta a \sin\theta$ or, neglecting the difference of R and a, $\Delta = \beta \sin\theta$ and the second with the axis coinciding with the direction $\varphi = (-45^\circ + \theta/2)$ for which $\Delta R = -\beta a \sin\theta$ or $\Delta = -\beta \sin\theta$. Applying (5A) and introducing successively $\delta = (\varphi - 45^\circ - \theta/2)$ and $\delta = (\varphi + 45^\circ - \theta/2)$ we find the following for the meridian QEP: $s_\rho = \beta R \sin\theta[\cos^2(\varphi - 45^\circ - \theta/2) - \cos^2(\varphi + 45^\circ - \theta/2)] = \beta R \sin\theta \sin(2\varphi - \theta)$. This is identical with (10). For the axis at right angles to this meridian plane the two deformations cancel each other, and so this is likewise in agreement to the case of a shift of the poles; this axis coincides with the axis of rotation of the crust, which does not change its length by the rotation.

This result permits a simple way of finding the solution of our problem; we can derive it from (5). For this purpose we introduce a system of polar coordinates δ, α with its axis coinciding with the axis of rotation of the crust; the origin of this system, therefore, lies in the equator. As it is shown in Figure 3, we reckon α from the great circle through the origin and the pole in its final position. The poles P_1 and P_2 of the above-mentioned systems of deformation according to (5) have latitudes of $(45° + \Theta/2)$ and $(-45° + \Theta/2)$ with regard to the initial position of the equator, and so their latitudes with regard to its final position are $(45° - \Theta/2)$ and $(-45° - \Theta/2)$; the coordinates of P_1 in the new system, therefore, are $\delta = 90°$ and $\alpha = (45° + \Theta/2)$ and of P_2 are $\delta = 90°$ and $\alpha = (135° + \Theta/2)$.

Introducing $\Delta = \beta \sin\Theta$ in the quantities σ_m and σ_r derived from the stresses σ_δ and σ_α of (5C) and (5D) we find

$$\left.\begin{aligned}\sigma_m &= (\sigma_\delta + \sigma_\alpha)/2 = [2m/(5m+1)]\beta E \sin\Theta[(2/3) - \sin^2\delta]\\ \sigma_v &= (\sigma_\delta - \sigma_\alpha)/2 = [m/(5m+1)]\beta E \sin\Theta \sin^2\delta\end{aligned}\right\}\quad\ldots\ldots\ldots\ldots (11)$$

This refers to the system of stresses around P_1; for the system P_2 we get the same formulas with opposite sign. The general formulas for the normal and tangential stresses working on a plane enclosing an angle μ with that of the principal stresses are $\sigma = \sigma_m + \sigma_v \cos 2\mu$ and $\tau = \sigma_v \sin 2\mu$. Introducing the denominations δ_1 and μ_1 for the system P_1 and δ_2 and μ_2 for the system P_2 as shown by Figure 3, we find σ_δ and σ_α for the combined systems P_1 and P_2 in our new coordinates as in the following formulas.

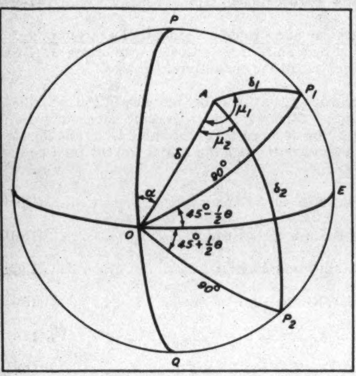


Fig. 3--System of stresses in spherical shell

$$\sigma_\delta = -[2m/(5m+1)]\beta E \sin\Theta(\sin^2\delta_1 - \sin^2\delta_2) + [m/(5m+1)]\beta E \sin\Theta(\sin^2\delta_1 \cos 2\mu_1 - \sin^2\delta_2 \cos 2\mu_2)$$

$$\sigma_\alpha = -[2m/(5m+1)]\beta E \sin\Theta(\sin^2\delta_1 - \sin^2\delta_2) - [m/(5m+1)]\beta E \sin\Theta(\sin^2\delta_1 \cos 2\mu_1 - \sin^2\delta_2 \cos 2\mu_2)$$

$$\tau = [m/(5m+1)]\beta E \sin\Theta(\sin^2\delta_1 \sin 2\mu_1 - \sin^2\delta_2 \sin 2\mu_2)$$

The angles AOP_1 and AOP_2 being $(45° - \alpha + \Theta/2)$ and $(135° - \alpha + \Theta/2)$ we can derive

$$\left.\begin{aligned}\sin\delta_1 \sin\mu_1 &= \sin(45° - \alpha + \Theta/2)\\ \sin\delta_2 \sin\mu_2 &= \sin(135° - \alpha + \Theta/2) = \sin(45° + \alpha - \Theta/2)\\ \sin\delta_1 \cos\mu_1 &= -\cos\delta \cos(45° - \alpha + \Theta/2)\\ \sin\delta_2 \cos\mu_2 &= -\cos\delta \cos(135° - \alpha + \Theta/2) = \cos\delta \cos(45° + \alpha - \Theta/2)\\ \cos\delta_1 &= \sin\delta \cos(45° - \alpha + \Theta/2)\\ \cos\delta_2 &= \sin\delta \cos(135° - \alpha + \Theta/2) = -\sin\delta \cos(45° + \alpha - \Theta/2)\end{aligned}\right\}\quad\ldots\ldots (12)$$

Introducing this in our formulas we obtain, after some reduction,

$$\sigma_\delta = [m/(5m+1)]\beta E \sin\Theta(\sin^2\delta + 2)\sin(2\alpha - \Theta)\quad\ldots\ldots\ldots\ldots (13A)$$

$$\sigma_\alpha = [m/(5m+1)]\beta E \sin\Theta(3\sin^2\delta - 2)\sin(2\alpha - \Theta)\quad\ldots\ldots\ldots\ldots (13B)$$

$$\tau = -[2m/(5m+1)]\beta E \sin\Theta \cos\delta \cos(2\alpha - \Theta)\quad\ldots\ldots\ldots\ldots (13C)$$

The value of σ_r follows from (1C)

$$\sigma_r = -[4m/(5m+1)]\beta E(T/R)\sin\Theta \sin^2\delta \sin(2\alpha - \Theta)\quad\ldots\ldots\ldots\ldots (13D)$$

For the components of the translation s we have to combine the values of s_ρ and of the components of s_δ of the systems P_1 and P_2 as given by (5A) and (5B) in which we introduce $\Delta = \beta \sin\Theta$ and $\Delta = -\beta \sin\Theta$, respectively. Thus

$$s_\rho = \beta R \sin\Theta(\cos^2\delta_1 - \cos^2\delta_2)$$

$$s_\delta = -[2(m+1)/(5m+1)]\beta R \sin\theta[\sin\delta_1\cos\delta_1\cos\mu_1 - \sin\delta_2\cos\delta_2\cos\mu_2]$$

$$s_\alpha = -[2(m+1)/(5m+1)]\beta R \sin\Theta[-\sin\delta_1\cos\delta_1\sin\mu_1 + \sin\delta_2\cos\delta_2\sin\mu_2]$$

By using the relations of (12) these reduce to

$$s_\rho = \beta R \sin\Theta \sin^2\delta \sin(2\alpha - \Theta) \tag{14A}$$

$$s_\delta = [2(m+1)/(5m+1)]\beta R \sin\Theta \sin\delta \cos\delta \sin(2\alpha - \Theta) \tag{14B}$$

$$s_\alpha = [2(m+1)/(5m+1)]\beta R \sin\Theta \sin\delta \cos(2\alpha - \Theta) \tag{14C}$$

Formulas (13) and (14) give the complete solution of our problem, namely, the stresses and deformations brought about in the rigid Earth's crust by a shift of the poles over an angle Θ. By introducing them in (1) and (2) we find that they indeed fulfill the conditions.

By choosing another origin for the coordinates, namely, half-way between the initial and the final position of the pole, we may obtain slightly simpler formulas, which in some cases may be useful for the investigation of our problem. They may be deduced along the same lines and do not present difficulties. Counting α with regard to the meridian through the initial and the final positions of the pole, we obtain (15) and (16).

$$\sigma_\delta = -[m/(5m+1)]\beta E \sin\Theta \sin 2\delta \cos\alpha \tag{15A}$$

$$\sigma_\alpha = -[3m/(5m+1)]\beta E \sin\Theta \sin 2\delta \cos\alpha \tag{15B}$$

$$\tau = [2m/(5m+1)]\beta E \sin\Theta \sin\delta \sin\alpha \tag{15C}$$

$$\sigma_r = [4m/(5m+1)]\beta E(T/R) \sin\Theta \sin 2\delta \cos\alpha \tag{15D}$$

$$s_\rho = -\beta R \sin\Theta \sin 2\delta \cos\alpha \tag{16A}$$

$$s_\delta = -[2(m+1)/(5m+1)]\beta R \sin\Theta \cos 2\delta \cos\alpha \tag{16B}$$

$$s_\alpha = [2(m+1)/(5m+1)]\beta R \sin\Theta \cos\delta \sin\alpha \tag{16C}$$

Before discussing our formulas and drawing conclusions we have to consider a point in connection with the assumptions from which we started our deductions; we have to prove that we were justified in neglecting the bending stresses in the crust. For this investigation we shall choose the bending of the meridian along which the pole has moved. The radius of curvature of the meridian is given by $\rho_m = a(1 - e^2)(1 - e^2\sin^2\varphi)^{-3/2}$ where $e^2 = (2\beta - \beta^2)$. If we indicate the variation of ρ_m caused by the deformation of the crust by Δ_ρ, the stress σ_f which because of the bending originates at the outer edge of a cross-section of the crust is

$$\sigma_f = (1/2)\Delta_\rho(T/\rho_m^2)E$$

Neglecting quantities of the order of the flattening we may substitute for ρ_m the mean Earth's radius R and for Δ_ρ

$$(\partial\rho_m/\partial\varphi)\Theta = 3\beta R\Theta \sin 2\varphi$$

We thus obtain

$$\sigma_f = (3/2)\beta E(T/R)\Theta \sin 2\varphi \tag{17}$$

This stress is of the same order of magnitude as σ_r and we have already argued that because of the smallness of the ratio (T/R) we may neglect it with regard to the main stresses σ_δ and σ_α.

For (5) in the case of a change of the flattening the same is true. The variation of ρ_m in this case is given by

$$(\partial\rho_m/\partial\beta) = -2a[1 - (3/4)\sin^2\varphi]$$

and so

$$\Delta_\rho = 2\Delta R[1 - (3/4)\sin^2\varphi]$$

and

$$\sigma_f = \Delta E(T/R)[1 - (3/4)\sin^2\varphi] \tag{18}$$

Comparing this with (5E) we see that again σ_ξ is of the order of σ_r and that we may neglect it with regard to σ_δ and σ_α.

Returning to the case of a shift of the pole we shall now examine the stresses that are brought about by it. For this purpose we shall use (13) based on an origin of the coordinates in the equator at a point coinciding with the axis of rotation of the crust. Equations (13A) and (13B) show that in two great circles through this origin given by $\alpha = \Theta/2$ and by $\alpha = (\Theta/2 + 90^\circ)$ the stresses σ_δ and σ_α disappear and we have pure shear. According to (13C) the shearing stress τ in these circles is maximum at the origin where the two circles intersect at right angles. The value τ_m of this maximum is

$$\tau_m = [2m/(5m + 1)]\beta E \sin \Theta \ldots\ldots\ldots\ldots (19)$$

Assuming the value of Θ of the shift of the pole to be 90°, which gives a maximum value of the deformation and the stresses, and introducing the values already adopted of $m = 4.1$ and $E = 1{,}000{,}000$ kg/cm^2, we find when using β at its present value of (1/297), $\tau_m = 1290$ kg/cm^2. This shearing stress is considerable and we may well imagine the crust to give way under its effect. In case the phenomenon has occurred at a very early date of the Earth's history it must even have been larger because the flattening must have been greater at that time. Using the value of flattening as (1/210) which Jeffreys derived for a date 1600 million years ago, we find $\tau_m = 1820$ kg/cm^2.

For the two great circles through the origin of the coordinates which bisect the right angles between the former pair and for which we, therefore, have $\alpha = (45^\circ + \Theta/2)$ and $\alpha = (-45^\circ + \Theta/2)$ we conclude from (13C) that τ disappears. The same is true for $\delta = 90^\circ$, namely, for the meridian along which the pole has moved. For this meridian we further find that everywhere $\sigma_\delta = 3\sigma_\alpha$, a result which we also may find at once by examining (15A) and (15B). σ_δ is here the normal stress in the meridian cross-section of the crust. The maximum absolute values of σ_δ are found in the crossings of this meridian with the two great circles, that is, for $\delta = 90^\circ$ and $\alpha = (45^\circ + \Theta/2)$ or $\alpha = (-45^\circ + \Theta/2)$; for the first it is a maximum tension and for the second a maximum compression. Their absolute values in both cases amount to

$$\sigma_{\delta m} = [3m/(5m + 1)]\beta E \sin \Theta \ldots\ldots\ldots\ldots (20)$$

and for $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, $\Theta = 90^\circ$, and $\beta = (1/297)$ this gives $\sigma_{\delta m} = 1930$ kg/cm^2. For $\beta = (1/210)$ we obtain $\sigma_{\delta m} = 2720$ kg/cm^2. We see again in this case that the stresses σ_δ and σ_α, as well as τ, do not depend on the thickness of the rigid crust; according to (13D) this only enters in the computation of the pressure σ_r exerted on the crust by the substratum.

In the crossings of the meridian $\delta = 90^\circ$, where we found that τ is zero with the two great circles $\alpha = \Theta/2$ and $\alpha = (\Theta/2 + 90^\circ)$ in which we saw that σ_δ and σ_α disappear, we have two points where all the stresses are zero. These points, therefore, are entirely free from stress.

Lastly it may be mentioned that from (13) we can conclude that the system of stresses has five planes of symmetry, namely, the meridian $\delta = 90^\circ$ and the four great circles through the origin, $\alpha = (\Theta/2 - 45^\circ)$, $\alpha = \Theta/2$, $\alpha = (\Theta/2 + 45^\circ)$, and $\alpha = (\Theta/2 + 90^\circ)$.

From our examination of the stresses it follows that probably the crust can not resist the stresses caused by a shift of the poles over a large angle. We have now to consider the question of how the crust will give way and along which lines we may expect this to occur. According to the theory of Mohr the break must take place in the cross-sections of maximum shear and in every point two such planes are present at right angles to each other. A newer theory of BYLAARD [1935, 1939] bearing on plastic deformation, since adopted also by VAN ITERSON [1943] supposes likewise two planes in each point, but these planes enclosing angles depending on the stresses. As the topography in many areas shows two predominating directions under angles different from 90° it seems likely that this last theory agrees better with the conditions in the Earth's crust. Bylaard himself has already brought it to bear on crustal problems and has given arguments for its validity in this case. He points out that although the materials of the crust at the surface are brittle, the great pressure in the major part of the crust must prevent the surpassing of the cohesion of the crystals, and that thus the deformation will take place by shear through the crystals and at higher values of the stresses; it thus must have a plastic character. As plastic deformation is characterized by conditions of flow the coefficient of Poisson in these parts may be expected to have a value of two.

Bylaard's theory on plastic deformation in elastic media is based on the supposition that in a thin plate on which only forces in its own plane are acting, plastic flow by preference must occur in a band of which in the length direction the dimensions are not changed, because otherwise the connection with the adjoining material would be severed and this would absorb a great deal of energy. Denoting the normal component of the stress in cross-sections of the plate parallel to the band by σ and at right angles to it by σ' and indicating the change in length per unit of length in both senses by ϵ and ϵ', Bylaard's condition amounts to $\epsilon' = 0$, which may be written $(1/E)(\sigma' - \sigma/2) = 0$, or

$$\sigma' = (1/2)\sigma \quad \ldots\ldots (21)$$

By means of the well-known relations we shall express σ and σ' in the principal stresses ρ_1 and ρ_2 and in the angle ψ enclosed between the band and the cross-section in which ρ_1 acts. Introducing

$$\rho_m = (1/2)(\rho_1 + \rho_2) \text{ and } \rho_v = (1/2)(\rho_1 - \rho_2) \quad \ldots\ldots (22A)$$

we have

$$\left.\begin{aligned} \sigma &= \rho_m + \rho_v \cos 2\psi \\ \sigma' &= \rho_m - \rho_v \cos 2\psi \end{aligned}\right\} \quad \ldots\ldots (22B)$$

and (21) becomes

$$(1/2)\rho_m - (3/2)\rho_v \cos 2\psi = 0$$

or

$$\cos 2\psi = (\rho_m/3\rho_v) = [(\rho_1 + \rho_2)/3(\rho_1 - \rho_2) \quad \ldots\ldots (22C)$$

Bylaard often writes this condition in the equivalent form

$$\tan\psi = \sqrt{(1 - \cos 2\psi)/(1 + \cos 2\psi)} = \sqrt{(3\rho_v - \rho_m)/(3\rho_v + \rho_m)} = \sqrt{(\rho_1 - 2\rho_2)/(2\rho_1 - \rho_2)} \quad . (22D)$$

Formulas (22C) or (22D) give the direction in which plastic flow will take place. For the case of pure shear, that is, when $\rho_2 = -\rho_1$ the angle ψ is $\pm 45°$, and so in this case Bylaard's theory coincides with that of Mohr; the plastic deformation occurs in the two planes of maximum shear. In other conditions, ψ assumes other values and the two theories diverge; in all cases, however, we find two values for ψ--one with positive sign and another of the same absolute value with negative sign. So in each point we obtain two planes of plastic deformation in symmetrical positions with regard to the planes of principal stress.

Van Iterson has extended Bylaard's theorem to the three-dimensional case. Maintaining the condition that the direction of the band in which plastic deformation occurs is such that it does not change its length we find the following formulas. When indicating the third principal stress by ρ_3, (21) becomes

$$\sigma' = (1/2)\sigma + (1/2)\rho_3 \quad \ldots\ldots (23)$$

and (22C) becomes

$$\cos 2\psi = [(\rho_1 + \rho_2 - 2\rho_3)/3(\rho_1 - \rho_2)] = [(\rho_1 - \rho_3) - (\rho_3 - \rho_2)]/3(\rho_1 - \rho_2) \quad \ldots (24A)$$

so (22D) changes to

$$\tan\psi = \sqrt{(\rho_1 - 2\rho_2 + \rho_3)/(2\rho_1 - \rho_2 - \rho_3)} = \sqrt{[(\rho_1 - \rho_2) - (\rho_3 - \rho_2)]/[(\rho_1 - \rho_2) + (\rho_1 - \rho_3)]} \, . (24B)$$

By writing the formulas in this way Van Iterson shows that ψ only depends on the differences of the principal stresses and not on their absolute values. This result sounds plausible; Bylaard has likewise pointed out that the superposition of an equal pressure in all directions may not be expected to affect the way in which plastic flow sets in. This is important for our problems regarding the Earth's crust; it makes it probable that the hydrostatic pressure in the crust does not influence the phenomena except in enforcing the plastic character of the deformation.

Van Iterson supposes that in general the planes of plastic flow must be parallel to the direction of the middle of the three principal stresses, or, in the terms of our formulas, that ρ_3 is the middle stress. There can be no doubt that in case the dimensions of the body are about the same in all directions this must be true. If we make use of the usual way of representing the stresses in the three-dimensional case by three circles (see Fig. 4), we see at once that the greatest shear is indicated by the circle belonging to the greatest and the smallest principal stresses, and so we may expect that plastic flow will occur in planes of which the position and the stresses are indicated by this circle, that is, in planes through the axis of the middle stress.

For the deformations of a plate of which the thickness is small with regard to the other dimensions, it seems probable that this may no longer be allowed. If Bylaard's supposition is valid, the condition of the dimension remaining the same must evidently be applied to directions in the plane of the plate, and so ρ_1 and ρ_2 in (24) must retain their meaning of indicating the stresses in normal cross-sections of the plate independent of their being or not being the greatest and smallest principal stresses; it is not necessary that the value of ρ_3 perpendicular to the plate lie between the values of ρ_1 and ρ_2. We shall see, for example, that for the stress conditions in the Earth's crust which we are investigating this is not everywhere the case. The question then arises whether in that case the plane of flow, which we know goes through the direction given by (24), may be expected to be perpendicular to the plate.

Dealing with this problem it is in general not possible to apply the same hypothesis of Bylaard for this direction and to suppose that the plastic flow will occur in a plane of which the dimensions in this sense likewise do not change; for an arbitrary stress situation there are no planes remaining entirely undeformed. We can think of two other suppositions instead, both of which we shall investigate. In the first place, we may suppose that in this sense the plane will be so situated that the shearing stress is a maximum, and in the second place, we may replace Bylaard's supposition of the dimensions remaining the same by a more general formula on the same base which can be fulfilled, namely, by the condition that the energy required in the boundary zone between the plastic and elastic areas must be a minimum. For thin plates, this last hypothesis must, no doubt, practically come to the same as the condition that in the direction of the plate the dimensions must remain unaltered; in a sense at right angles the plane must adjust itself so that the energy is a minimum. We shall see that both suppositions lead to the possibility of planes of shear not normal to the plate. For the Earth's crust the formation of inclined planes has its consequences; it must lead to vertical movements on both sides of the shear. If there is compression in this plane, this must in itself give rise to such movements, and in case of tension vertical movements must be brought about by the readjustment of the isostatic balance.

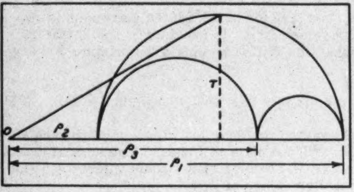


Fig. 4--Graphical presentation of stresses in three-dimensional case

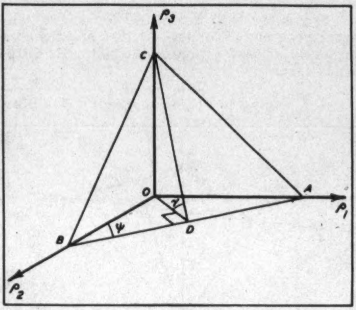


Fig. 5--Shear in plane cutting horizontal plane

For investigating the hypothesis of maximum shear we shall first derive the formula for the shear in an arbitrary plane in the direction given by (24). In Figure 5 the three axes represent the directions of the stresses ρ_1, ρ_2, and ρ_3, AOB represents the plane of the plate, the angle OBA represents the angle ψ given by (24A) or (24B), and AB, therefore, is a line of flow. ABC is an arbitrary plane through AB making an angle γ with the plane of the plate. We want to determine the shearing stress $\tau_{\psi\gamma}$ in this plane.

The normal to ABC makes angles α, β, and γ with the directions ρ_1, ρ_2, and ρ_3. According to the well-known trigonometrical formula we have $\cos\alpha = \sin\gamma\cos\psi$ and $\cos\beta = \sin\gamma\sin\psi$, and so the three components, parallel to the axis, of the stress working on ABC are $\rho_1 \sin\gamma\cos\psi$, $\rho_2 \sin\gamma\sin\psi$, and $\rho_3 \cos\gamma$. Determining the two components of $\tau_{\psi\gamma}$, namely, τ_{AB} in the direction of AB and τ_{cd} in the direction of the perpendicular CD on AB we find

$$\tau_{AB} = (\rho_1 - \rho_2)\sin\psi\cos\psi\sin\gamma = [(\rho_1 - \rho_2)/2]\sin 2\psi\sin\gamma$$

$$\tau_{CD} = (\rho_1\cos^2\psi + \rho_2\sin^2\psi - \rho_3)\sin\gamma\cos\gamma = (1/2)\Big\{(\rho_1+\rho_2)/2 + [(\rho_1-\rho_2)/2]\cos 2\psi - \rho_3\Big\}\sin^2\gamma$$

and by means of (24A)

$$\tau_{CD} = (1/3)(\rho_1 + \rho_2 - 2\rho_3)\sin^2\gamma$$

This gives

$$\tau^2_{\psi\gamma} = (1/4)(\rho_1 - \rho_2)^2\sin^2 2\psi\sin^2\gamma + (1/9)(\rho_1 + \rho_2 - 2\rho_3)^2\sin^2 2\gamma$$

and using (24A)

$$\tau^2_{\psi\gamma} = [(1/4)(\rho_1 - \rho_2)^2 - (1/36)(\rho_1 + \rho_2 - 2\rho_3)^2] \sin^2\gamma + (1/9)(\rho_1 + \rho_2 - 2\rho_3)^2 \sin^2 2\gamma \ldots (25)$$

By differentiating this with regard to γ and equating the result to zero we find that the maximum value $\tau_{\psi\gamma m}$ of the shear occurs for

$$\cos 2\gamma = (1/16)\left\{1 - 9[(\rho_1 - \rho_2)/(\rho_1 + \rho_2 - 2\rho_3)]^2\right\} \ldots\ldots\ldots\ldots (26A)$$

which may also be written

$$\cos 2\gamma = -(1/16)\tan^2 2\psi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (26B)$$

The corresponding value of the maximum shear is

$$\tau_{\psi\gamma m} = (1/16)\left\{5 + 3[(\rho_1 - \rho_2)/(\rho_1 + \rho_2 - 2\rho_3)]^2\right\}(\rho_1 + \rho_2 - 2\rho_3) \ldots (27A)$$

or

$$\tau_{\psi\gamma m} = (1/3)(\rho_1 + \rho_2 - 2\rho_3)\sin^2\gamma \ldots\ldots\ldots\ldots\ldots\ldots (27B)$$

Examining (26B) we see that for $\psi >$ arc tan 4, that is, for $\psi > 75°58'$ the maximum is no longer real, and so for these values of ψ the greatest value of $\tau_{\psi\gamma}$ is found for $\gamma = 90°$, that is, for normal cross-sections of the plate. By introducing this in (25) we obtain the maximum shear in this case.

$$\tau_{\psi\gamma m} = \sqrt{(1/4)(\rho_1 - \rho_2)^2 - (1/36)(\rho_1 + \rho_2 - 2\rho_3)^2} = (1/2)(\rho_1 - \rho_2)\sin 2\psi \ldots (28)$$

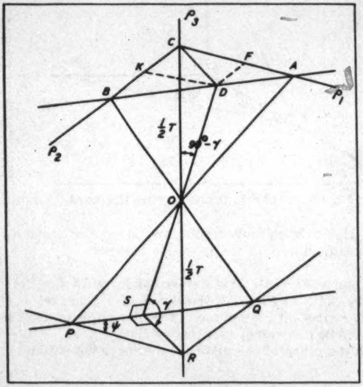


Fig. 6--Diagram of plane of flow

So we find that only for values of ψ between 45° and 38° the plate will shear along normal cross-sections. Table 1 shows some values of γ for smaller values of ψ.

According to the second hypothesis the plane of flow adjusts itself in such a way that the energy required in the boundary zone between the plastic and elastic areas is minimum. If the plane ABC of Fig. 6 represents the upper and PQR the lower surface of the crust, O a point on the ρ_3 axis in the middle of the crust (OC = OR = T/2), PQOAB the plane of flow, and SD as well as CD perpendicular to AB, we may suppose this energy to be proportional to the surface of the plane of flow between AB and PQ, that is, to SD, and also to the square of the component in PQOAB of the displacement of D with regard to O. Denoting this displacement by Δ and its components in the sense of the ρ_1, ρ_2, and ρ_3 axis by Δ_1, Δ_2, and Δ_3, we have

$$\left.\begin{aligned} E\Delta_1 &= [\rho_1 - (1/2)\rho_2 - (1/2)\rho_3] \times KD = (1/2)T[\rho_1 - (1/2)\rho_2 - (1/2)\rho_3]\cos\psi\cot\gamma \\ E\Delta_2 &= [\rho_2 - (1/2)\rho_1 - (1/2)\rho_3] \times FD = (1/2)T[\rho_2 - (1/2)\rho_1 - (1/2)\rho_3]\sin\psi\cot\gamma \\ E\Delta_3 &= (1/2)T[\rho_3 - (1/2)\rho_1 - (1/2)\rho_2] \end{aligned}\right\} \ldots (29)$$

If Δ_γ indicates the component of Δ in the plane OAB, we obtain by making use of these formulas and of (24A)

$$\Delta^2_\gamma = (9/64)(T^2/E^2)(\rho_1 - \rho_2)^2 \sin^2 2\psi \cot^2\gamma + (1/16)(T^2/E^2)(\rho_1 + \rho_2 - 2\rho_3)^2(\cos^2 2\gamma/\sin^2\gamma) \ldots\ldots\ldots\ldots (30)$$

By multiplying this by SD = T cosec γ and using (24A) again, we find that the energy mentioned above must be proportional to

$$T\Delta^2_\gamma \operatorname{cosec} \gamma = (1/64)(T^3/E^2)(\rho_1 + \rho_2 - 2\rho_3)^2[16 \sin \gamma - (16 + \tan^2 2\psi)(1/\sin \gamma) + (4 + \tan^2 2\psi)(1/\sin^3\gamma)] \quad (31)$$

So our problem reduces to finding the value of γ which renders the last factor a minimum. By differentiating with regard to γ and equalling to zero we thus obtain

$$\sin^2 \gamma = -(1/2)[1 + (1/16)\tan^2 2\psi] + (1/2)\sqrt{[1 + (1/16)\tan^2 2\psi]^2 + 3[1 + (1/4)\tan^2 2\psi]} \quad (32)$$

It is simple to prove that this gives indeed a minimum value of the energy.

By introducing $\sin \gamma = 1$ we find the maximum value of ψ providing a real solution; we thus obtain $\tan^2 2\psi = 10$ and $\psi = 36°14'$. For all values of ψ between 45° and this limit the minimum energy is given by $\gamma = 90°$ or, in other words, the planes of flow according to our supposition must be normal to the crust. For all smaller values of ψ we get inclined planes.

Some results are given in Table 1 by (24A), (26A), and (32) for different values of the ratio $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$. The first line contains the corresponding values of ψ, the second the values of γ_1 as given by (26A) for the hypothesis of maximum shear, and the third the values of γ_2 as provided by (32) for the last hypothesis.

Table 1--Values of ψ, γ_1, and γ_2 for various values of ratio $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$ computed from (24A), (26A), and (32)

Computed value	For $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$ equal to						
	1/2	2/3	5/6	1	7/6	4/3	3/2
	° ′	° ′	° ′	° ′	° ′	° ′	° ′
ψ	45 00	41 49	38 44	35 16	31 48	28 08	24 06
γ_1	90 00	90 00	90 00	60 00	52 21	49 02	47 14
γ_2	90 00	90 00	90 00	74 20	60 10	53 55	50 14

We see that the results of the two hypotheses do not differ much; in both cases the planes of flow are inclined with regard to the plane of the plate in case ψ is below a certain limit, 38° in the first case and 36°14′ in the second. It is not possible to make sure which of the two hypotheses is nearer to the truth, but if the shear planes in the Net obey the formula of Bylaard, as seems to be the case for the Earth's crust, it appears reasonable to prefer the second, which is in better harmony with Bylaard's hypothesis than the first. Only experimental evidence for different values of the ratio $[(\rho_1 - \rho_3)/(\rho_1 - \rho_2)]$ can give us basis for a sound decision on this matter; in this way only we may hope to obtain an answer to the question whether one of the two hypotheses can be adopted. As Van Iterson indicated to the writer in connection with the extensive investigation he has made on the subject of plastic deformation, the problem is extremely complicated and far from ripe for a final settlement. For the phenomena in the Earth's crust an additional difficulty arises from the circumstance that relative vertical movements on both sides of the shear plane, as they may be expected for an inclined plane, must bring about flow in the plastic substratum. This will absorb energy and it might, therefore, be possible that this change of the conditions also affects the course of events. It is clear that for the areas where under all circumstances normal planes may be expected, this complication is not present nor is there any uncertainty about the position of the plane.

We shall now apply our results to the problems of the Earth's crust, in the first place to the stresses caused by a shift of the pole. For this purpose we have to derive the principal stresses and the corresponding planes. We know that ρ_3 acting on planes parallel to the plate is zero. For deducing ρ_1 and ρ_2 we shall use (13). The angle μ between the direction of ρ_1 and the great circle through the origin of the coordinates belonging to these formulas--the point where the axis around which the crust has rotated cuts the equator--is given by

$$\tan 2\mu = 2\tau/(\sigma_\delta - \sigma_\alpha) = -[2 \cos \delta/(1 + \cos^2 \delta)] \cot(2\alpha - \theta) \quad (33)$$

By means of this value of μ we can derive ρ_1 and ρ_2 from

$$\left.\begin{aligned} \rho_1 &= (\sigma_\delta + \sigma_\alpha)/2 + [(\sigma_\delta - \sigma_\alpha)/2] \sec 2\mu \\ \rho_2 &= (\sigma_\delta + \sigma_\alpha)/2 - [(\sigma_\delta - \sigma_\alpha)/2] \sec 2\mu \end{aligned}\right\} \quad (34)$$

Introducing these values in (24A) and using (13A), (13B), and (13C) we obtain

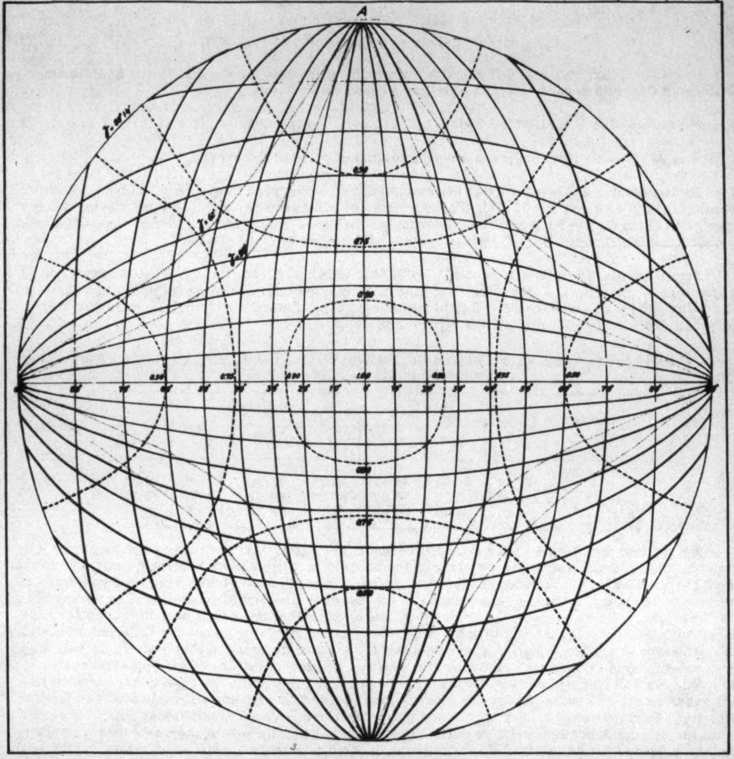


Fig. 7--Shear pattern in stereographic projection of the half sphere for infinitesimal shift of the poles; for shift over the angle θ the figure has to be rotated clockwise over $\theta/2$. The dashed lines indicate shear intensity; the dotted lines the possible angle of the shear planes with the crust

$$\cos 2\psi = (1/3)[(\sigma_\delta + \sigma_\alpha)/(\sigma_\delta - \sigma_\alpha)] \cos 2\mu = (2/3)[\sin^2\delta/(1 + \cos^2\delta)]\cos 2\mu \quad (35)$$

If ψ represents the positive angle corresponding to this formula, the angles between the two planes of shear and the great circle through the origin are $(\mu + \psi)$ and $(\mu - \psi)$. So (33) and (35) provide us with the position of the planes of shear in each point. Figure 7 gives the results of the computations for a half sphere around the origin of the coordinates. It has been drawn in stereographic projection, and the pole is found on the circumference at an angular distance of $\theta/2$ to the left of the point A; to bring it in the normal position with horizontal equator the Figure, therefore, must be turned clockwise over an angle $\theta/2$. In the position of Figure 7 the angle $(\alpha - \theta/2)$ is counted clockwise from the radius through A.

From (33) and (35) it follows that Figure 7 has four axes of symmetry, namely, $(\alpha - \theta/2) = -45°$, $0°$, $45°$, and $90°$; this corresponds to the axis mentioned above regarding the stresses. We further find that for $(\alpha - \theta/2) = 0°$ or $90°$, $\mu = 45°$ and $\psi = 45°$ and $(\mu + \psi) = 90°$ and $(\mu - \psi) = 0°$. For $(\alpha - \theta/2) = \pm 45°$ we have $\mu = 0°$ and $\cos 2\psi = (2/3)[\sin^2\delta/(1 + \cos^2\delta)$. For $\delta = 90°$ independent of α, $\mu = 90°$, $\cos 2\psi = (2/3)$, and $\psi = 24°06'$; and $(\mu + \psi) = 114°06'$ and $(\mu - \psi) = 65°54'$.

So in the meridian, at the border of the Figure, the angles the two shear directions make with the radius towards O are everywhere ± 65°54′.

By means of the results given by (33) and (35) for $(\mu + \psi)$ and $(\mu - \psi)$, in a good many points two systems of curves have been drawn in Figure 7 representing the shear curves over the Earth's surface. These systems show four singular points, namely, A, B, C, and D, where the curves converge. The value of ψ at these points is indeterminate; this corresponds to the stresses being zero there.

Two other systems of curves have been drawn in Figure 7. In the first place we find the stippled curves which connect the points where, according to the second hypothesis, the inclination γ of the shear planes with regard to the plane of the crust is 60° or 90°; in the area inside the last curves we have $\gamma = 90°$, and so here the shear planes are everywhere normal to the crust. These curves have been derived by means of (32) and a formula expressing ψ in δ and α, which may be derived from (33) and (35). By making use of (15A), (15B), and (15C) instead of (13A), (13B), and (13C) it is easy to prove that these curves are characterized by the property that at an arbitrary point E the angle ψ as well as the angle between the great circles connecting E with A and B are constant along the same curve. The last angle is halved by the direction of the principal stresses in E.

In the second place we have the broken curves connecting the points where the critical stress is equal to 90 per cent, 75 per cent, and 50 per cent of the maximum value found at O. For these deductions we have adopted the hypothesis of HUBER [1904] and HENCKY [1924], according to which the plastic flow begins to occur when the stress σ_v given by

$$\sigma_v{}^2 = (1/2)[(\rho_1 - \rho_2)^2 + (\rho_2 - \rho_3)^2 + (\rho_1 - \rho_3)^2] \ldots\ldots\ldots\ldots \tag{36A}$$

surpasses a certain critical value. For our case we have $\rho_3 = 0$, and so we obtain

$$\sigma_v{}^2 = \rho_1{}^2 - \rho_1 \rho_2 + \rho_2{}^2 = (1/4)(\rho_1 + \rho_2)^2 + (3/4)(\rho_1 - \rho_2)^2 \ldots\ldots\ldots \tag{36B}$$

Introducing in this formula the stresses σ_δ, σ_α, and τ instead of ρ_1 and ρ_2 we find

$$\sigma_v{}^2 = (1/4)(\sigma_\delta + \sigma_\alpha)^2 + (3/4)(\sigma_\delta - \sigma_\alpha)^2 + 3\tau^2$$

and by means of (13A), (13B), and (13C)

$$\sigma_v{}^2 = \left\{ [m/(5m + 1)]\beta E \sin\theta \right\}^2 [7 \sin^4\delta \sin^2(2\alpha - \theta) + 12 \cos^2\delta] \ldots\ldots\ldots \tag{37}$$

The first factor is constant over the Earth's surface, and the second variable factor attains a maximum value of 12 for $\delta = 0$, that is, for the origin 0 of the coordinates in Figure 7. So σ_v attains its maximum σ_{vm} at this same point. The ratio of σ_v in an arbitrary point to this maximum is

$$\sigma_v/\sigma_{vm} = \sqrt{(7/12) \sin^4\delta \sin^2(2\alpha - \theta) + \cos^2\delta} \ldots\ldots\ldots\ldots \tag{38}$$

The dotted curves of Figure 7, representing values of 90 per cent, 75 per cent, and 50 per cent of this ratio have been computed by means of this formula. They give an idea about the parts of the Earth's crust that must first be liable to plastic flow along the curves of the Net. Inside the curve for 50 per cent it seems less likely that plastic deformation has taken place.

The maximum value of the critical stress at O is given by

$$\sigma_{vm} = [m\sqrt{12}/(5m + 1)]\beta E \sin\theta \ldots\ldots\ldots\ldots\ldots\ldots \tag{39}$$

and introducing the values of page 10: $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, $\theta = 90°$, and $\beta = (1/297)$ we find $\sigma_{vm} = 2230$ kg/cm^2 and for $\beta = (1/210)$, $\sigma_{vm} = 3150$ kg/cm^2. These values confirm our viewpoint that probably the crust can not have borne the stresses without giving way; they exceed the limits we may expect to be valid for the crustal materials.

By means of Figure 7 we can determine the Net of shear curves over the Earth's surface for each value of θ. Choosing the corresponding situation of P we may draw the net of meridians and parallels in stereographic projection and we are free to give the point O any longitude we wish. If this geographic net is sufficiently dense it is easy to change over to another projection; we have simply to transfer the points of intersection of the shear curves with the meridians and parallels and the curves can be drawn. Net 1 has been done on a Mercator projection. In order to adjust the directions of the shear curves as well as possible to the prevalent directions of topography of the North Atlantic in azimuths of about 65° west and 45° east [VENING MEINESZ, 1942], the value of θ has been fixed at 70° and the longitude of O at 0° Greenwich. This last choice allows a range of not much more than 10° without injuring the correlation. It is simple to check this by moving Net 1 with regard to the map in a horizontal sense. For the angle θ the correlation is even more sensitive; a rotation of Figure 7 over 5° clearly lessens it. The azimuth of the bisector of the angle between the two directions in the North Atlantic adopted at 10° is undoubtedly greater than 5° and smaller than 15°.

It might well be possible that, since the breaking catastrophe of the crust, it has further moved around the Earth. In fact, it is likely that the forces causing the motion up to that moment have continued to work. We have two possibilities in this connection--either these forces have again been able to move the crust as a whole or this has not been the case. The latter possibility might be explained by the supposition that the energy for moving the systems of blocks into which the crust has been divided is larger than for the unbroken crust because of the friction between the blocks. Especially if we assume that the movement has been brought about by subcrustal currents, we may expect a strong tendency towards differential motion of the blocks, and so the latter possibility does not seem unlikely. If, however, the crust has continued to move, the pole must have undergone a contrary motion with regard to the crust of the same size. The component φ_1 of this movement in the sense of the border meridian of Figure 7 alters the angle POA and so, for a certain value of this angle derived from the topographic evidence, the angle θ described before the catastrophe must have been so much less that

$$\text{Angle POA} = \varphi_1 + \theta/2 \; . \; . \; . \; . \quad (40A)$$

If there has been a component φ_2 of the motion at right angles to the border meridian, the pole has reached a position outside the border meridian as indicated in Figure 8. The geographic net of meridians and parallels in stereographic projection through P can be constructed as before, and we may again transfer Figure 8 to Mercator projection. Net 2 shows the result thus obtained for $\varphi_2 = 10°$. As is shown in the next paragraph, we find that the correlation to the topography of this Net is less than for Net 1, and if we repeat the procedure with $\varphi_2 = -10°$, that is, with a motion of the pole in the opposite sense, we find it still worse. So it appears probable that there has been no appreciable movement of the pole in this sense after the crustal breaking.

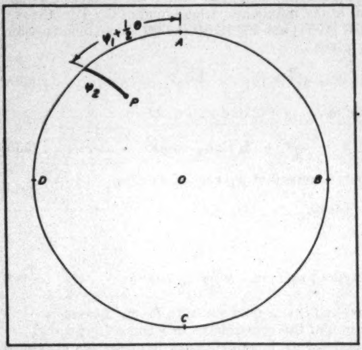


Fig. 8--Position of pole outside border meridian

Summarizing, we find that a movement φ of the pole after the catastrophe is possible but that it must have occurred mainly in the same great circle as before. The angle θ described before the breaking is given by

$$\theta = (70° - 2\varphi_1) \; . \quad (40B)$$

We have already remarked that this motion of the pole over the angle θ may have taken place along the border meridian of Figure 7, but that this need not have been the case. If, however, the path has deviated from this circle, the distance from the initial position can not have attained a value of θ or more at some intermediate moment, because that would have led to the breaking of the crust along another net. We may conclude that, except for this reservation, the determination of the location of the shearing net over the Earth's surface in the position mentioned above allows only the conclusion that the initial position of the pole and the position at the breaking moment must both have been situated on the meridian of 90° east, at least for positive values of φ_1 smaller than 70°, and that their mutual distance θ is given by (40B). If there has been no later movement φ_1 of the pole, the angle θ must have been 70°, and so the initial position of the pole was 20° nort in 90° east, that is, near Calcutta. If such a movement had taken place, θ could have been smaller but it must have had a value sufficiently large to lead to the breaking of the crust. In this case the total angle described by the pole was

$$(\theta + \varphi_1) = (70° - \varphi_1) \; . \quad (41)$$

and so the initial position of the pole must have been $(20° + \varphi_1)$ north in 90° east.

A last problem to be taken up is the question of the forces needed for the rotation of the crust. These forces consist of two parts: First, that which is required for the increase of the stresses dealt with in this Chapter, and second, the part needed for the overcoming of the friction at the lower boundary of the crust. In view of the nearly complete adjustment of the isostatic equilibrium of the crust, there seems to be reason to expect that the second part will be relatively small, but it is difficult to arrive at a reliable estimate of its order of magnitude. We can affirm, however, that if we assume that the forces causing tectonic movements in parts of the crust are brought about by subcrustal currents, those same currents must be able to bring about a gliding of the whole crust over the Earth; from this standpoint it is likely that such movements are possible. Another argument for assuming its possibility may be found in the usually adopted viewpoint that, at a sufficiently great depth, the materials of the Earth react in a purely viscous way, and that, therefore, even the smallest momentum will bring about motion, although the speed will be proportionally small. If this viewpoint is rigorously true, this part of the forces required might even be quite negligible.

The first part can be derived from the formulas of this Chapter. We may determine the deformation energy from the formula

$$A = [(m+1)/2mE](\sigma_x^2 + \sigma_y^2 + \sigma_z^2) + [(m+1)/mE](\tau_x^2 + \tau_y^2 + \tau_z^2) - (1/2mE)(\sigma_x + \sigma_y + \sigma_z)^2$$

which in our case reduces to

$$A = [(m+1)/2mE](\sigma_\delta^2 + \sigma_\alpha^2) + [(m+1)/mE]\tau^2 - (1/2mE)(\sigma_\delta + \sigma_\alpha)^2$$

Introducing (13) and integrating over the whole crust we find

$$A = (32/15)[m/(5m+1)]\pi E\beta^2 TR^2 \sin^2\theta \ldots\ldots\ldots\ldots\ldots\ldots \quad (42)$$

Formula (42) agrees with that found by Kuiper for m = 3 in his study of shifts of the pole caused by the "Polfluchtkraft" [KUIPER, 1943, p. 86].

Differentiating this formula with regard to θ we find the momentum of forces, M, required to increase the angular distance θ from the initial position of the pole is as in (43).

$$M = (32/15)[m/(5m+1)]\pi E\beta^2 TR^2 \sin 2\theta \ldots\ldots\ldots\ldots\ldots\ldots \quad (43)$$

For this deduction we have assumed that the motion of the pole occurs along the great circle connecting its initial and final positions, and that, therefore, M works around the axis perpendicular to the plane of this great circle, that is, around the same axis around which θ is measured. If the axis of the momentum has another position, the rotation of the crust around this axis over an angle $d\epsilon$ will be larger than the increase $d\theta$ of θ, and the formula for M has to be multiplied by $(d\theta/d\epsilon)$; this factor is always smaller than unity.

According to (43) the maximum value of M occurs for $\theta = 45°$. Introducing again $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, $\beta = (1/297)$, T = 30 km, and R = 6371.2 km we find that this maximum is $M_{max} = 1.76 \times 10^{20}$ kg km, and for $\beta = (1/210)$ this maximum is $M_{max} = 3.53 \times 10^{20}$ kg km. These values do not represent momentums of improbable magnitude. If we should have a subcrustal current in an area near the equator able to bring about a compression in the crust of 100 kg/cm^2 over the whole thickness of the crust of 30 km and over a horizontal extension of 1000 km, this would represent a momentum of

$$M = 6370 \times 30 \times 1000 \times 100 \times 10^{10} = 1.9 \times 10^{20} \text{ kg km}$$

As a stress of 100 kg/cm^2 is no doubt only a small fraction of the stress required to bring about a tectonic deformation, we may expect that the currents needed for such phenomena will be more than powerful enough to give rise to the elastic deformation of the crust accompanying shifts of the crust around the Earth.

The momentum of the "Polfluchtkraft" found by KUIPER [1943] for the present period is $M_p = 3 \times 10^{19}$ kg km and for the maximum value in former periods $M_{p\,max} = 3.5 \times 10^{19}$ kg km. We see that if the values of E adopted in this paper are right, this value is not sufficient to expect the "Polfluchtkraft" to have played a prominent part in possible movements of the crust around the Earth. It is, however, not negligible, and this result, already found by Kuiper, is interesting; although the "Polfluchtkraft" is so small that it cannot by its direct action bring about larger stresses in the crust than a few kg/cm^2, it is able, if the friction at the lower boundary of the crust is negligible, to give rise to fairly great shifts of the poles with accompanying crustal deformation stresses of hundreds of kg/cm^2. For the present flattening the equation $Mp_{max} = M$ gives, according to (43) a value of θ of about 6°, and this corresponds to a maximum stress $\sigma_{\delta m}$ of about 200 kg/cm^2. It is even clear that in case a greater value of θ already exists because of other causes, the "Polfluchtkraft" may still bring about increases of θ provided the axis of its momentum does not coincide with the axis about which θ is measured, and the corresponding factor $(d\theta/d\epsilon)$ mentioned above is small enough to reduce M below the value of Mp. Lastly we may remark that the "Polfluchtkraft" at a very early date of the history of the Earth's crust may have been larger than the present topography accounts for; in fact we know nothing about the topography in those early periods. So we may conclude that although it is probable that the "Polfluchtkraft" has not been the principal agent in bringing about the rotation of the crust around the Earth, it is possible that it has contributed to it.

Returning to the problems connected with a change of the flattening we have still to investigate the way we may expect the shearing of the crust to occur when the limit the crust can stand is exceeded. We know in this case the planes in which the principal stresses work; they are the normal cross-sections of the crust through the parallels and the meridians. The principal stresses themselves are given by (5C) for σ_δ and (5D) for σ_α. Adopting again Bylaard's and Van Iterson's theory about the direction of the shearing planes, we shall apply (22C) to obtain the angle ψ these planes make with the meridian; we introduce $\rho_1 = \sigma_\alpha$ and $\rho_2 = \sigma_\delta$. We thus find

$$\cos 2\psi = -(2/3)[(\cos^2\delta - 1/3)/\sin^2\delta] = (4/9)[(3/2) - \operatorname{cosec}^2\delta] \quad \ldots\ldots\ldots (44)$$

For $\delta = 90°$, that is, for the equator, we find $\psi = \pm 38°35'$ and for $\delta = 54°44'$, that is, $\varphi = 35°16'$, we have $\psi = \pm 45°$ and so at this latitude the two shearing planes enclose right angles. For $\delta = 31°05'$, that is, for $\varphi = 58°55'$, the value of ψ is $\pm 90°$ and so here the two directions both coincide with the direction of the parallel. For larger values of φ, (44) no longer gives real solutions, and so according to this Formula no shearing is possible here. The meaning of this result is that in this area no directions can be found for which the length dimension remains unaltered during the deformation, and so Bylaard's hypothesis leads to the conclusion that no shearing can occur.

Figure 9 shows the Net in Mercator projection as it follows from (44). It is not in good agreement with the directions of the topography over the Earth's surface. In the North Atlantic, for example, it does not show the asymmetry of the two directions with regard to the north direction. We could improve it by assuming that, since the shearing, a small shift of the crust around the interior has taken place. Net 3 has been derived from Figure 9 by adopting a shift of the North Pole over 10° in the sense of the meridian of 90° west of Greenwich. In this way the asymmetry of the Net in the North Atlantic is brought into harmony with that of the topography. In Chapter III we shall find, however, that this Net is still far from showing the same correlation to the topography over the Earth's surface as that given by the hypothesis of a shift of the poles.

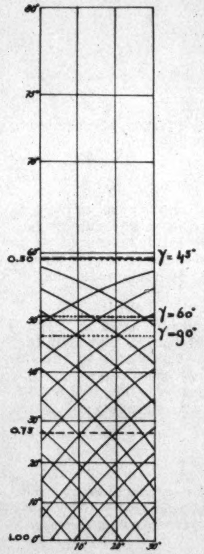


Fig. 9--Shear pattern in Mercator projection for a change of the flattening. The dashed lines indicate shear intensity; the dotted lines the possible angle of the shear planes with the crust

Figure 9 shows two other systems of lines besides the curves of the shearing net; they correspond to the curves in Figure 7. The stippled lines indicate the points where the shear planes have the same inclination with regard to the plane of the crust. To derive this angle we have again adopted the second hypothesis about this point, according to which the inclination, γ, of the planes is such that the energy spent in the boundary zone between the elastic and the plastic deformation is a minimum. We have applied (32), therefore, to find the value of ψ corresponding to a certain value of γ and then (44) to derive the latitude, φ, at which this occurs. We thus obtained for values of $\gamma = 90°$, 60°, and 45°, values of $\varphi = 47°20'$, 50°48', and 58°55', respectively. At all latitudes below 47°20' the angle γ is 90°, that is, the shear planes are normal to the crust.

The second set indicated by broken lines gives the points where the critical stress σ_v has a value of 75 per cent and 50 per cent of the maximum value found for $\varphi = 0$. They may give an idea where shearing

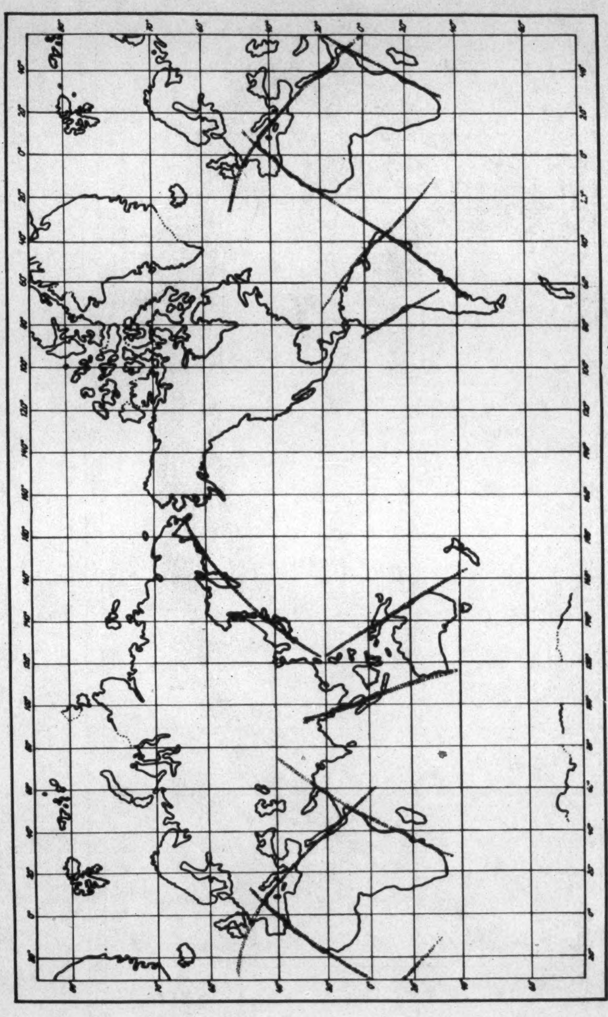


Fig. 10--Supposed major shear zones of the Earth's crust

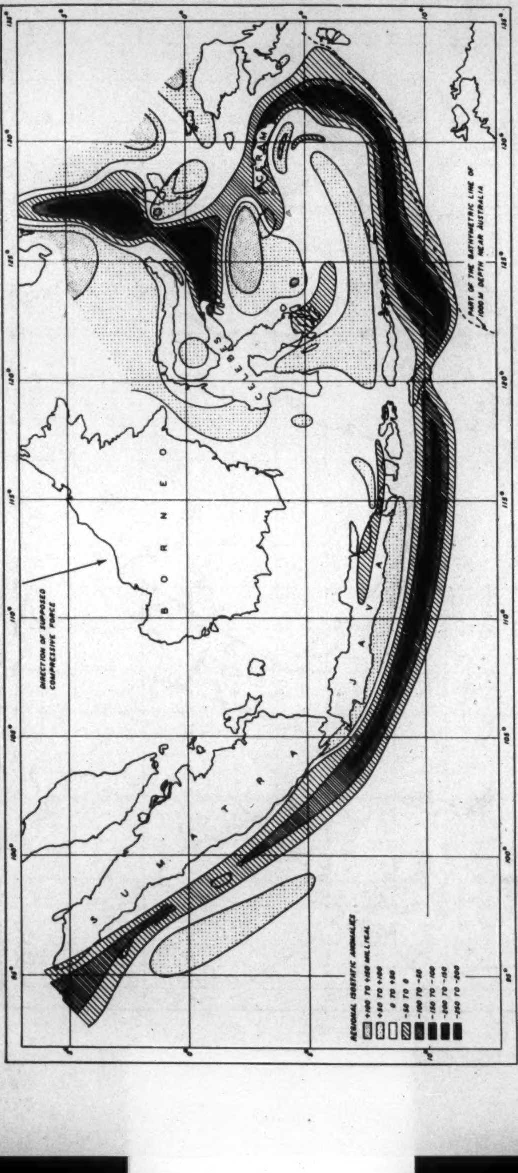

DIRECTION OF SUPPOSED COMPRESSIVE FORCE
B O R N E O
C E L E B E S
CERAM
S U M A T R A
J A V A
PART OF THE BATHYMETRIC LINE OF 1000 M DEPTH NEAR AUSTRALIA
REGIONAL ISOSTATIC ANOMALIES
+100 TO +150 MILLIGAL
+50 TO +100
0 TO +50
-50 TO 0
-100 TO -50
-150 TO -100
-200 TO -150
-250 TO -200
95°
100°
105°
110°
115°
120°
125°
130°
135°
5°
0°
5°
10°

Fig. 11--Gravity anomalies in Dutch East Indies

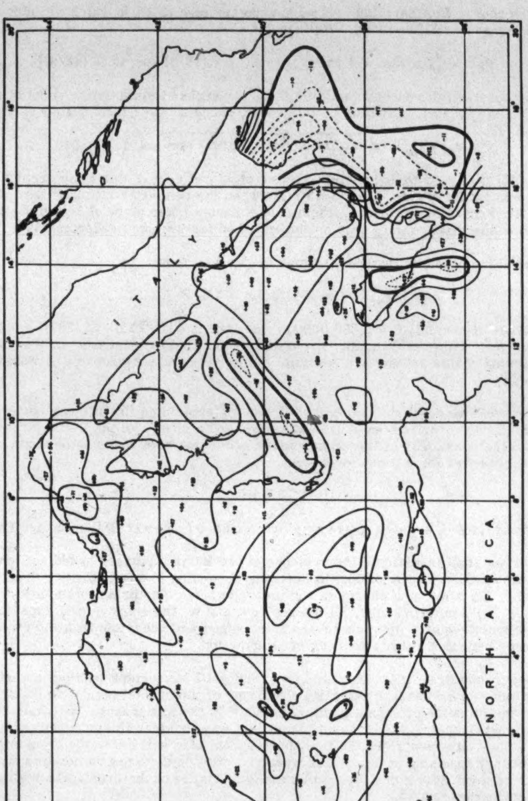

ITALY
NORTH AFRICA

Fig. 12--Gravity anomalies in Mediterranean Area is most likely to occur. For deriving σ_v we have again used (36B) in which we introduced $\rho_1 = \sigma_\alpha$ and $\rho_2 = \sigma_\delta$ given by (5D) and (5C). We thus obtain

$$\sigma_v^2 = \left\{[m/(5m + 1)]\Delta E\right\}^2[7 \cos^4 \delta - (26/3) \cos^2 \delta + (31/9)] \ldots\ldots (45)$$

The first factor is constant, the second variable; the last reaches its maximum value of (31/9) for $\delta = 90°$, that is, for the equator. Dividing by this value, changing over from δ to φ and taking the square root we get

$$\sigma_v/\sigma_{vm} = \sqrt{(63/31) \sin^4 \varphi - (78/31) \sin^2 \varphi + 1} \ldots\ldots (46)$$

By means of (46) it is easy to deduce that a value of 75 per cent of this ratio occurs for $\varphi = 27°13'$ and of 50 per cent for $\varphi = 45°$ and $58°55'$. Between the two latter latitudes the ratio has a minimum value. As, according to this hypothesis, no shearing takes place at higher latitudes than 58°55′, we may conclude that shearing may not be expected for latitudes exceeding 45°.

The maximum value of the critical stress may be deduced from

$$\sigma_{vm} = [(m\sqrt{31})/3(5m + 1)]\Delta E \ldots\ldots (47)$$

Introducing the values of $m = 4.1$, $E = 1{,}000{,}000$ kg/cm^2, and $\Delta = [(1/210) - (1/297)] = 0.00140$ we find $\sigma_{vm} = 500$ kg/cm^2. This result confirms our conclusion that the stresses in the case of a change of the flattening of this amount are not quite sufficient to make probable a world-wide breaking catastrophe.

In this Chapter we have dealt with two possibilities for explaining the bilinear pattern of extensive parts of the Earth's surface--a shift of the poles and a change of the flattening. We have not yet investigated the possibility of these phenomena occurring both at the same time. This investigation may be reserved for a future occasion.

CHAPTER III

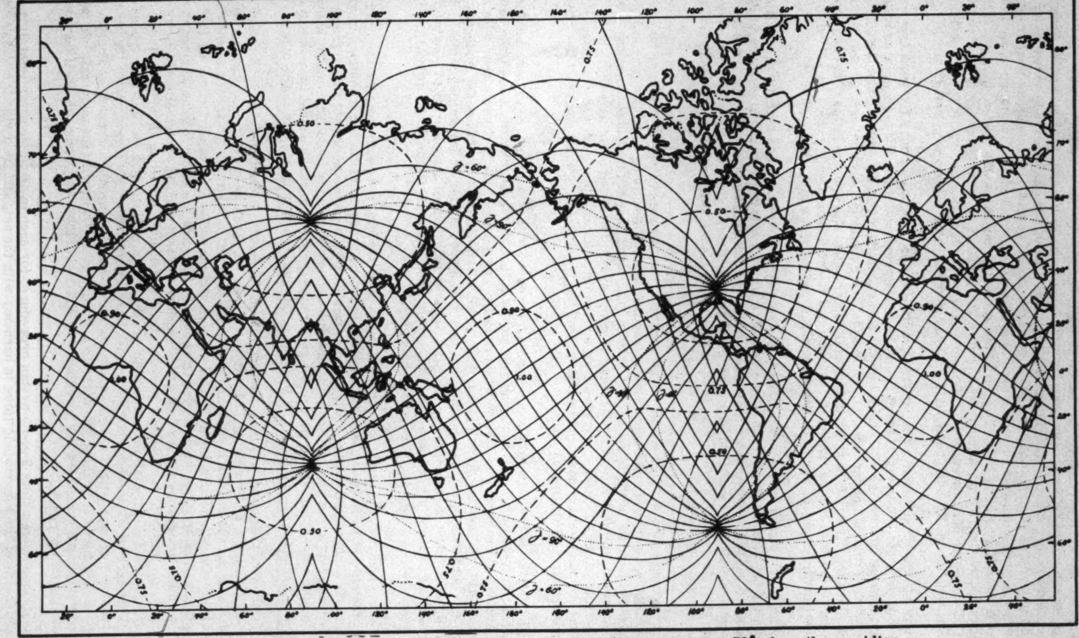
The Evidence at the Earth's Surface of Nets of Fault Planes in the Crust

In this Chapter we shall investigate the evidence at the Earth's surface shedding light on the question whether the crust has been subject to shearing according to one of the two hypotheses of this paper--a shift of the poles or a change of the flattening. We may bring this evidence under three heads, namely; (a) the topography, (b) the geology, and (c) the geophysical, especially the gravimetric and seismic results; the second are more vague and uncertain than the others. We shall briefly examine here these three sources of information.

Taking the topography first, it is clear that practically all phenomena leading to vertical movements of the crust must bring about differential elevations of the crustal blocks on both sides of a fault plane, and so the situation of such a plane must show in the topography. We shall come back to this point in the next Chapter. A second and important way in which the topography is affected is brought about by the volcanism along the fault planes; this also will cause the disclosing of these planes at the surface. Especially in the oceans where no erosion disturbs the topography we may consider the latter as a valuable guide for finding the fault planes of the crust. Geological evidence is practically absent in these parts.

For the continents the problem is more complicated. In the first place erosion so strongly influences the topography that in many cases it must obliterate the effects of fault planes or at least render them more difficult to read, although in the detailed topography it may help to divulge them because of the infiltration of water in the clefts and frost effects. In the second place the topographic evidence is supplemented here by the geological data, which in many cases will give a more direct and more positive indication of the presence of shear planes than any other evidence can provide. So, for most continental areas, no final conclusions can be drawn without a thorough geological study of the data.

Considering these circumstances, the writer, not being a geologist, has refrained from attacking the problem for the continents; he restricted himself to a statistical investigation of the submarine topography. As this is fairly well known over about one-half of the Earth's surface, this source of information gives a good approach to the problem. We shall find that it shows a remarkably strong correlation to Net 1 and so indicates a polar shift along the meridian of 90° east as mentioned above. The other two Nets show less correlation.


0.50
0.75
0.90
1.00
∂=60°
∂=90°
20°
0°
40°
60°
80°
100°
120°
140°
160°
180°

Net 1--Shear pattern in Mercator projection for a shift of the poles over 70° along the meridian of 90° longitude. The dashed lines show shear intensity; the dotted lines the possible angle of the shear planes with the crust

As for the evidence on the continents we need not altogether leave it out of our considerations; a great mass of data regarding the presence of fault planes--not known to the writer when he undertook this investigation--already has been brought together by geologists such as Hobbs, Sederholm, Daubrée, and Sonder, who in their lineament tectonical publications have already given many indications in favor of a world-wide shearing net of the Earth's crust. In the second part of this Chapter we shall discuss how far these results are in agreement with Net 1, and we shall find agreement for nearly all the instances. As this material has been discovered independently of any theory and as thus a biased judgment is out of the question, we may consider it as a striking support of our polar shift hypothesis. The same may be said of Krenkel's results for the African Continent, which have likewise been dealt with and which also fit remarkably well in Net 1.

Turning to the geophysical evidence, the gravity field in some cases may likewise give valuable data for our problem. In the first place it discloses the trend of subterranean structures which, evidently, may be correlated with crustal shear planes. In the second place, for areas where great buckling of the crust has occurred, as, for example, the East Indian Archipelago, it can provide evidence about the direction in which the crustal compression has operated; this direction may also be connected with the fracturing of the crust and in the East Indies it indeed coincides with one of the two directions of our Net. We shall come back to these and other points.

The seismic results may give indications in two ways. In areas where records of a sufficiently numerous set of seismological stations are available we may obtain the position in space of the fault planes along which movements take place. Such results are thus restricted to areas in land or in archipelagoes and we can not expect through seismic data to find large parts of the shearing net of the Earth's crust. Obviously we thus can only find planes along which movements are still active in the present period.

In the second place it may be possible in certain areas, where geological evidence for shearing is also available, to combine the epicenters of earthquakes in lines along which we may suppose the shearing movement of the crust to proceed. In the second part of this Chapter we shall examine the maps made in this way by Sieberg for many areas; for the greater part their lines are in good harmony with our Net. So by means of such maps, although more or less conjectural in themselves, we may get valuable confirmation about the location of the fault planes of the crust where movements are still going on.

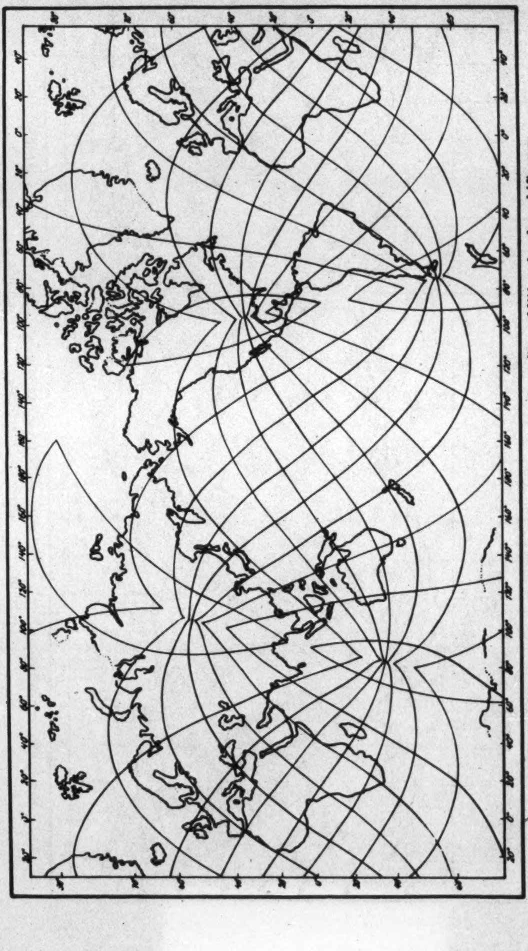
In studying the correlation of the submarine topography with Net 1 we have to bear in mind that this Net is based on a few simplifying assumptions, that is, the uniform thickness, the homogeneity, and the isotropism of the Earth's crust, which are certainly not absolutely true. We have to expect, therefore, that the shear planes of the crust will not accurately follow the mathematical net which has been deduced; it is probable that they will show smaller or larger deviations. For taking this into account in the following investigation we shall neglect angles up to 12° between topographic features and directions of the Net, or, in other words, if the deviation is smaller than that limit we shall consider them as still in harmony.

One of the best ways to study the correlation, no doubt, would be to construct in each area a rose for which the radii in the different directions would be proportional to the frequency of this direction in the topographic features; these roses would allow a good estimate of the degree of correlation with Net 1. In general, however, the submarine topography is not sufficiently known in detail to give a basis for such a procedure in a limited area; as it is we should have to extend the area so far that the directions of the Net would vary too much from one end to the other.

We shall have, therefore, to follow another line of research. After careful consideration of the problem the writer arrived at the following solution. For each area determine the sum of the lengths of the topographic lines in harmony with the Net and also for the lines agreeing with the two sets of directions bisecting the angles of the Net; in both cases neglect deviations up to 12°. By taking the ratio of the first sum divided by the second we obtain a value for comparing the correlations with the topography for both sets of directions. If this ratio is systematically larger than the unity, we may affirm that Net 1 has at least a correlation equalling this ratio. If the bisecting net has itself a correlation with the topography, the correlation of Net 1 is correspondingly greater. This case is not to be excluded, because in extensive areas the directions of the bisecting net coincide more or less with the north-south and east-west directions, and many geologists think that at least the first of these two directions occurs more frequently than normal. So by adopting our ratio as a figure for the correlation of Net 1 with the topography, we shall certainly not over-estimate our result.

We shall also submit Nets 2 and 3 to this procedure; for each of them we shall determine the sum of the lengths of the topographic lines in harmony with the net, and we divide the result by the same quantity as used for the comparison of Net 1, that is, by the sum of the topographic lines in agreement with the bisecting directions of Net 1. These last determinations need not be made with the same care as for Net 1; it is sufficient to obtain a precision allowing the conclusion that the correlation with the topography of these Nets is smaller than that of Net 1.

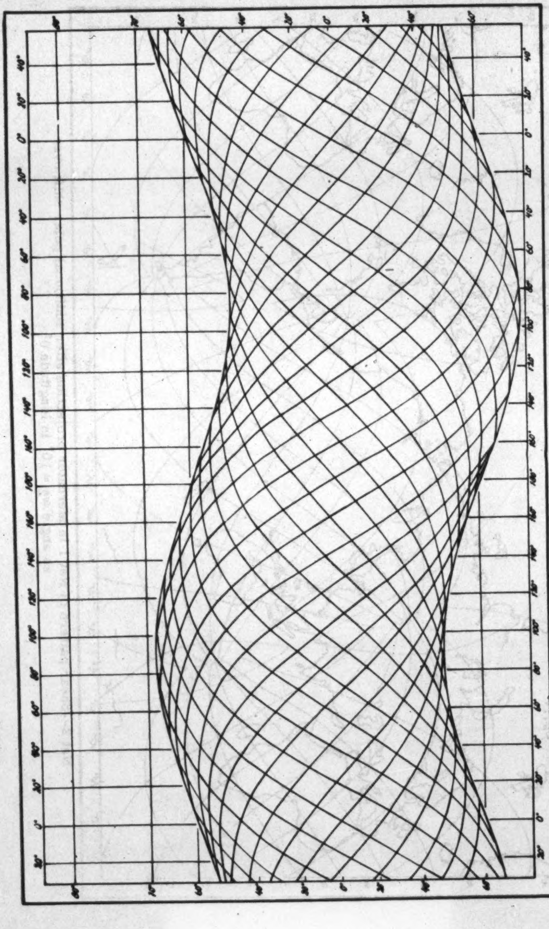
For these determinations we shall use only charts with contour lines at intervals of a thousand meters or less. As the tracing of these lines is often more or less uncertain, we shall give a weight of one-half to a topographic feature indicated by only one of these lines. For ridges we shall count the two slopes separately; a ridge bordered on both sides by parallel slopes will receive, therefore, a double weight, unless on each side it is only indicated by one contour line; in



Net 2--Shear pattern of Net 1 in Mercator projection after additional polar shift over an angle $\varphi_2 = 10^\circ$ in longitude 0°

this last case the weight is equal to unity. We shall not count each contour line separately with the same weight, as we might perhaps be tempted to do, because we thus would give undue weight to the slopes extending over great differences in depth. As we have already mentioned, we shall assign a weight of one to each slope indicated by at least two contour lines. We shall not take account of slopes of less than 500-meter difference of depth, and so in shallow seas and over coastal shelves, where we usually have contour lines at short depth intervals, we shall in general not include any lines.

For our investigation we shall successively survey the following areas: the North Atlantic, the South Atlantic, the Mediterranean combined with the Red Sea, the Black Sea, and the Caspian



Net 3--Shear pattern of Fig. 9 for change of flattening in Mercator projection after additional polar shift of 10° along the meridian of 90° longitude

Sea, the Indian Ocean, the North Pacific, and the South Pacific. In the Arctic Sea the number of soundings is insufficient for our purpose and the same is true for the seas surrounding the Antarctic Continent--for these seas we can only remark that the general trend of the deep basins does not contradict the directions of Net 1.

For the North Atlantic a fairly detailed depth survey has been made to high latitudes and so we can extend our investigation from the Equator up to latitude 70° north. The writer employs a new chart of the North Atlantic to be published shortly in a report on the gravity observations at sea; it extends from 0° up to 50° north latitude. It has been drawn by J. W. Bloem of the Hydrographic Office of the Netherlands Navy, who compiled it from the third edition of the "Carte Bathymétrique des Oceans" [to be henceforth indicated by "Monaco chart" supplemented by the number of the edition] corrected to 1940 from various sources, that is, mainly from United States Hydrographic Charts Nos. 5486 and 5487 and from soundings by the Altair in 1938 [DEFANT, 1939; WÜST, 1939]. North of 50° we can use the Monaco chart (3rd ed.) and the "Tiefenkarte der Dänemark Strasse, Irminger See, u. s. w." of G. Bönecke [1936].

For the South Atlantic the writer has used the chart of the Meteor Expedition [BORN, date not noted], which extends farther south than the third edition of the Monaco chart. He investigated the area from 0° to 60° south latitude and from 65° west to 25° east.

The Mediterranean, the Red Sea, the Black Sea, and the Caspian Sea have been studied by means of the Monaco chart.

For the northwestern part of the Indian Ocean the writer used the chart of the "John Murray Expedition" [WISEMAN, date not known] and for the remainder, the Monaco charts. These last parts are only poorly surveyed, especially at higher latitudes, and so the writer restricted the investigation to the part north of 45° south latitude further limited by the meridians of 25° east and 145° east. West of the meridian of 90° east, he used the third edition of the Monaco chart but east of it the second edition. In the last part he could supplement this evidence by the soundings of the submarine Hr. Ms. K XVIII of the Netherlands Navy taken during its expedition of 1934-35; it gave rise to some changes in the tracing of the contour lines.

For the study of the North Pacific the writer could use the provisional edition of the chart of the United States Hydrographic Office of 1939, which was kindly given to him during his stay in Washington for the Seventh General Assembly of the International Union of Geodesy and Geophysics in 1939. It is a remarkable improvement on previous charts, which was rendered possible by more than 180,000 new echo soundings made by vessels of the United States Navy in recent years. It thus gives a fairly detailed representation of the submarine topography over a great part of this ocean. The chart extends to 5° south latitude, and the writer, therefore, extended his survey of the North Pacific to this same latitude.

For the South Pacific no other charts were available than the second edition of the Monaco charts and, as in the eastern and southern parts of this ocean the depth figures are scarce and the tracing of the contour lines uncertain, the writer did not extend the investigation further than to 135° west longitude and to 45° south latitude for the part west of longitude 175° west and to latitude 30° south for the part between longitudes 135° west and 175° west. For the western limit the meridian of 145° east was taken.

With only one exception the charts used are drawn on Mercator projection, and so the directions are not distorted. Only the "Tiefenkarte der Dänemarkstrasse, u. s. w." is represented in another, not conformal, projection; this has been taken into account as well as possible. For measuring the lengths on the charts, the areas have been divided in horizontal strips of 10° or 15° breadth, and for each strip the lengths have been totalled and the sum multiplied by a common reduction factor corresponding to the mean value for this strip. The figures for the Red Sea, although combined with those of the Mediterranean, have been reduced separately. Table 2 summarizes the results for all these determinations. The columns successively give the sum L_1 of the lengths in correlation with Net 1, L_2 for Net 2, L_3 for Net 3, and L_4 for the bisecting net of Net 1. The last three columns contain the ratios (L_1/L_4), (L_2/L_4), and (L_3/L_4). The last line of each subdivision of Table 2 gives the sums of L_1, L_2, L_3, and L_4 and the ratios of these sums; it thus provides us with the result for the whole ocean. Table 3 puts together the results for the different oceans; in a first column the measured areas have been added.

Table 2--Summary of lengths on charts for latitude intervals

Latitude interval	L_1	L_2	L_3	L_4	(L_1/L_4)	(L_2/L_4)	(L_3/L_4)
° °	km	km	km	km			
North Atlantic Ocean, from 0° to 70° north latitude							
70 N - 60 N	7100	7100	0	2300	3.08	3.08	0.00
60 N - 50 N	5300	5300	1800	2900	1.83	1.83	0.62
50 N - 40 N	11200	11200	5700	4000	2.80	2.80	1.42
40 N - 30 N	17400	17400	10900	5000	3.48	3.48	2.18
30 N - 20 N	13500	13500	12000	4400	3.07	3.07	2.73
20 N - 10 N	6200	6200	5500	2300	2.69	2.69	2.39
10 N - 0	10900	10900	5000	2200	4.95	4.95	2.27
Totals	71600	71600	40900	23100	3.10	3.10	1.77
South Atlantic Ocean, from 0° to 60° south latitude and 65° west to 25° east longitude							
0 - 15 S	10100	10100	9000	5800	1.74	1.74	1.55
15 S - 30 S	10700	10700	10700	6100	1.75	1.75	1.75
30 S - 45 S	10600	10600	10600	4300	2.46	2.46	2.46
45 S - 60 S	7800	7800	6300	3400	2.29	2.29	1.85
Totals	39200	39200	36600	19600	2.00	2.00	1.87
Mediterranean, Red Sea, Black Sea, and Caspian Sea							
-- --	15500	15500	8800	7200	2.15	2.15	1.22
Indian Ocean to 45° south latitude and 25° east to 145° east longitude							
25 N - 0	29000	13100	19300	9600	3.02	1.36	2.01
0 - 15 S	14300	10900	14300	7500	1.91	1.45	1.91
15 S - 30 S	13700	9400	7500	3300	4.15	2.85	2.27
30 S - 45 S	11100	10700	3500	3000	3.70	3.57	1.17
Totals	68100	44100	44600	23400	2.91	1.88	1.90
North Pacific Ocean from 60° north to 5° south latitude							
60 N - 45 N	10700	10700	1600	3100	3.45	3.45	0.52
45 N - 30 N	18400	18400	12500	8200	2.25	2.25	1.53
30 N - 15 N	32100	32100	18200	13200	2.43	2.43	1.38
15 N - 5 S	29500	27500	29500	16400	1.80	1.68	1.80
Totals	90700	88700	61800	40900	2.22	2.17	1.51
South Pacific Ocean from 5° south to 45° south latitude and 145° east to 175° west longitude and from 5° south to 30° south latitude and 175° west to 135° west longitude							
5 S - 15 S	18300	18300	18300	8500	2.15	2.15	2.15
15 S - 30 S	15400	15400	10100	12400	1.24	1.24	0.81
30 S - 45 S	6900	6900	6900	3900	1.77	1.77	1.77
Totals	40600	40600	35300	24800	1.64	1.64	1.42

Table 3--Summary of Table 2 for oceans and areas

Ocean or group	Area	L_1	L_2	L_3	L_4	(L_1/L_4)	(L_2/L_4)	(L_3/L_4)
	$10^6 km^2$	km	km	km	km			
North Atlantic	35.2	71600	71600	40900	23100	3.10	3.10	1.77
South Atlantic	40.5	39200	39200	36600	19600	2.00	2.00	1.87
Mediterranean, Red Sea, Black Sea, Caspian Sea .	8.5	15500	15500	8800	7200	2.15	2.15	1.22
Indian Ocean	49.8	68100	44100	44600	23400	2.91	1.88	1.90
North Pacific to 5° south. .	86.8	90700	88700	61800	40900	2.22	2.17	1.51
South Pacific south of 5° south	28.8	40600	40600	35300	24800	1.64	1.64	1.42
Totals	249.6	325700	299700	228000	139000	2.34	2.16	1.64

The last line of Table 3 contains the sums of the areas and of the lengths L_1, L_2, L_3, and L_4 in the (L_1/L_4), (L_2/L_4), and (L_3/L_4) ratios; these ratios are not the mean values of the corresponding columns.

We see that the total of the areas surveyed is $250 \times 10^6 km^2$; as the whole surface of the Earth is $510.1 \times 10^6 km^2$, our determinations have covered practically one-half of it. This is sufficient, no doubt, for attributing great weight to our evidence. We shall, in the first place, use this evidence for the comparison of the three Nets. For the third Net, which corresponds to a change of the flattening, our conclusion can be simple; it is clear that its correlation with the topography is less than for Net 1. This is especially clear for those parts of the oceans where the nets differ most, that is, for high latitudes. For the belts of 70° to 60° and 60° to 50° of the North Atlantic we find ratios for Net 3 of 0.00 and 0.62, while Net 1 shows 3.08 and 1.83. The ratio 0.00 for Net 3 indicates that this Net does not show lines at all between 60° and 70°, while Net 1 in this area shows a correlation of 3.08; this is evidently strongly in favor of Net 1. For the belt of 30° to 45° of the Indian Ocean we find 1.17 for Net 3 against 3.70 for Net 1; for the belt of 60° to 45° of the North Pacific the values are 0.52 against 3.45. Only the value 1.85 for the belt of 45° to 60° of the South Atlantic shows less difference with the ratio 2.29 of Net 1. For the South Pacific the area that was investigated does not reach the latitude where the Nets differ much. Considering these results we may safely conclude that the hypothesis of a change of the flattening does not fit the evidence as well as that of a shift of the poles. We shall not investigate the former any further in this or the next Chapter.

The question whether Net 1 or Net 2 shows the greater correlation with the topography has less importance for the study of the history of the Earth; both Nets are based on the same hypothesis of a shift of the poles and the only point is whether, since the shearing catastrophe, the pole has slightly wandered in a sense at right angles to the plane of symmetry of the shearing net. The evidence does not give much support for this last supposition. Although the ratios for Net 2 differ less from those of Net 1 than those of Net 3, one of the two areas where the Nets deviate most from each other shows evidence in favor of Net 1. These areas are situated near and over the meridians of 90° east and 90° west and the Indian Ocean provides a ratio of 1.88 for Net 2 against 2.91 for Net 1. The second oceanic part that could have given information is the southeastern Pacific, but in this area not enough is known of the topography to allow a determination of the correlation. For the Northern Hemisphere the meridians of 90° east and 90° west are located on the continents. We may conclude that the evidence, as far as it goes, is in favor of Net 1, but that this conclusion is less decisive than for the comparison to Net 3. We shall henceforth keep to Net 1 in our subsequent discussions.

Examining Tables 2 and 3 we see that for all the areas the ratio for Net 1 is greater than unity; in Table 3 it varies from 1.64 to 3.10. This is obviously a strong indication that the correlation to the topography is not fortuitous. This conclusion is further supported by the fact that the two highest values of 3.10 and 2.91 have been found for those oceans where the topography is best known, namely, the North Atlantic and the Indian Ocean. For the latter much of the information is based on soundings of the "John Murray Expedition" in the northwestern part. For the Mediterranean the topography is likewise known in detail, but the ratio is somewhat less. We may perhaps explain this by the fact that this area belongs to a zone of tectonic folding, and that this part of the topography does not depend directly on the shearing net. It is likely that this same explanation may be given for the relatively small value of the ratio for the southwestern Pacific.

We might ask whether it is possible to obtain an impression of the probability that no real cause would be behind our correlation, or, in other words, that these values of the ratio only accidentally deviate from unity. If no special directions dominate in the submarine topography, we may expect the value of this ratio to tend to this last value, and we might suppose that deviations from it would follow Gauss's law of probabilities. On this basis we may make an estimate as follows. According to Gauss's law the probability of a deviation between x and (x + dx) is given by $ydx = (1/m\sqrt{2\pi})e^{-x^2/2m^2}dx$, in which m is the mean value of the deviations. This last quantity is unknown in our case. We shall meet this difficulty by deriving the maximum value this probability can assume if m varies. By differentiating the formula with regard to m and equating the differential quotient to zero we find m = x, and as the second differential quotient is negative for this value, it is a maximum. Introducing this value of m in the above formula we obtain

$$y_m dx = (1/\sqrt{2\pi e})(dx/x) = 0.24(dx/x) \qquad (48)$$

To apply this formula to our problem we introduce for x the deviation of the mean value of (L_1/L_4) from unity for a special area, for example, the North Atlantic, and for dx the range between the extreme values of this quantity. This last substitution is, of course, a rough procedure, but as we require only an approximate estimate of the probability, we may permit it. According to our choice of m we find a maximum value for this probability.

Applying our formula to the North Atlantic we thus obtain for the probability that a value of (L_1/L_4) is inside the total range $y_m dx = (0.24)(3.12/2.10) = 0.36$, and for the probability that the seven values are all inside this interval we find $0.36^7 = 0.00078$. If we restrict our deductions to the Atlantic between 10° north and 70° north, we have a range of the ratios of 1.65 and we obtain $y_m dx = (0.24)(1.65/2.10) = 0.19$, and for six values inside this range $0.19^6 = 0.000047$. We see that these probabilities are quite negligible, and so we may conclude that the presence of a dominating system of directions coinciding inside limits of 12° to both sides with our Net is practically a certainty if at least the writer has not, unconsciously, been too much biased in making the measurements. For the other areas we get the same result; for the South Pacific the probability is largest, but even here we find only 0.041, and so we may still neglect it. We come, therefore, to the conclusion that over all the oceans investigated, that is, over half of the Earth's surface, the topography shows a predominance of the directions corresponding to a shift of the poles as assumed.

The great number of topographic features in correlation with our Net produces in itself a problem. We may ask whether it is likely that the Earth's crust under the stresses caused by a shift of the poles will give way in so many places. It is difficult to give a positive answer to this question, because the physical properties of the Earth's crust as a whole are so imperfectly known, but we may probably find a satisfactory explanation by comparing our case to the behavior of steel under stresses exceeding the yield value. If a flat strip of steel is subjected to a slowly increasing tension, plastic deformation sets in at a certain moment and this may be made visible, for example, by polishing the surface; the deformed section then discloses itself by the dimming of the surface. The experiments show that after such a line has formed, the plastic deformation stops at this place and a second one forms, obviously because the deformation has led to a "hardening" of the matter at the former place. In this way a great number of such lines may form in quick sequence to each other. In case the tension is further increased, breaking will occur at one of the sections, but it can not be predicted where this will be. A similar phenomenon might be imagined to occur in the Earth's crust, which, because of the great pressure in its major part, may be expected to behave as a plastic material.

Another point difficult to decide by theoretical deduction is the question how far and how the deformation will proceed in the areas of smaller stress around the points of zero stress where the curves of the Net converge. It is clear that if the crust has yielded to plastic deformation over great distances the stresses near these points may have increased and may have led to deformations in these areas too, but the distribution of stress may have been changed, and so in this case we may expect other lines of shear. Concluding, we can not suppose Net 1 to be valid for these areas. As, however, we find several topographic features correlated to this Net inside the curves where the critical stress has reached half its maximum value, these areas of non-correlation seem to be restricted to a still more limited extent. We may mention the following examples: The west coast of Australia; the coast of California; and the edge of the shelf northwest of the Bahamas.

One of the most difficult problems connected with the hypothesis of a shift of the poles is the explanation of the correlation of the shearing net and the continental coasts, which the map seems to indicate. It is especially desirable, therefore, to make sure how far this correlation is present. We shall begin here by a statistical investigation along the same lines as made above, but as the lengths of the coast line of each continent are rather small for this purpose, we can not attach too much importance to the figure obtained for the separate continents; for all the continents taken together the results carry more weight.

For our purpose we require the course of the structural boundaries of the continents, that is, of the edges of the continental shelves. As this course is uncertain for the coasts surrounding the Arctic Sea and likewise those of the Antarctic Continent, we shall not include them in our investigation.

In measuring the coast lines in harmony with the directions bisecting the angles of our Net, the writer got the impression that they occurred with greater than normal frequency, and that this figure thus did not provide us with a good basis for comparison. He repeated, therefore, the procedure for the Net given by the meridians and the parallels and found that this sum was indeed smaller than the former for all the continents. Table 4 gives the ratios of the sum L_1' of the coast lines in harmony with Net 1 to the sums L_2' and L_3' for both comparison nets; L_2' refers to the north-south and east-west directions, L_3' to the bisecting directions of Net 1. Nets 2 and 3 have not been investigated.

Table 4--Correlation of the continental coast lines to Net 1

Continent	L_1'	L_2'	L_3'	(L_1'/L_2')	(L_1'/L_3')
	km	km	km		
Eurasia	15780	9010	9050	1.75	1.74
North America	12330	5940	7390	2.08	1.67
South America	11180	7320	7430	1.53	1.51
Africa	8380	6260	7140	1.34	1.17
Australia	8070	4880	7340	1.65	1.10
Totals	55740	33410	38350	1.67	1.45

The coast lines of Eurasia and North America have been measured up to 60° north latitude, and those of Central America have been added to North America. The coasts of the Mediterranean, the Black Sea, the Caspian Sea, and the Red Sea have been omitted, because we can not consider them as having the character of the edge of a continent. For the same reason, all island ridges have been left out. For eastern and southeastern Asia, as elsewhere also, the edge of the shelf has been followed, and so the continental block carrying Sumatra, Java, and Borneo has been included. In the same way New Guinea and Tasmania have been added to Australia. The coasts of New Zealand have not been measured.

Examining the results we see that the correlation is decidedly less than shown by the previous tables for the submarine relief, in which, it may be remarked here, the continental edges have been included. As the differences of L_2' and L_3' for the two Nets of comparison are small, we can not definitely affirm that the bisecting Net has a correlation with the coast lines, although it is possible that this is true. As this remains uncertain, it does not appear justified to prefer the value of 1.67 to that of 1.45 for the ratio of L_1' to the sum of the lengths in harmony with an arbitrary net, and so we shall take the mean of these values, that is, 1.56. Comparing this to the value of 2.34 found above for the submarine topography we see that the deviation from unity is less than half of this last value. Still, it does not seem doubtful that for the continental coasts a correlation exists also, and this is confirmed by applying Formula (48). Taking the mean of the values of the last two columns of Table 4 for each continent, the largest of these figures is 1.88 and the smallest 1.26, and so we may introduce for dx the difference 0.62. We thus obtain, in case we should assume no correlation at all, that the maximum probability of a value of the ratio occurring between these two limits is $(0.24)(0.62/0.56) = 0.265$, and of five values inside this same range $0.265^5 = 0.0013$.

This result does not leave much doubt that a correlation really exists. We may remark, however, that our statistical investigation can only be considered as a first superficial attack of the problem; for a more thorough study we shall have to take into account what we know about the origin of these coast lines. For many of these this is not much, but for all those where we find folded mountain ranges parallel to the coast or where such formations have been present in former periods, we may at least suspect their general trend to have been determined by these phenomena. If we examine the evidence in this regard, we find that only part of these coast lines is in harmony with the Net. For this study the following coasts are to be considered: The west coast of North, Central, and South America; part of the east coast of North America; great parts of the east coast of Asia; the major part of the block limited by Sumatra, Java, and Borneo; part of the coast of

Burma and the Malay States; the south coast of Baluchistan; the northeast coast of Queensland; the west coast of Tasmania and Victoria; the coast of Natal and a small part of the west coast of South Africa near Cape Town. Perhaps we ought to add the edge of the European Shelf from Bayonne to west of Lands End and also northwest Ireland and Scotland, but, as this is questionable, it has not been included. If we measure the lengths of the coast lines here enumerated as far as they are in harmony with the Net and also as far as they agree with the bisecting directions, we find the sum of the first lengths to be $L_1'' = 22930$ km and of the second $L_2'' = 14680$ km. The ratio is 1.56. This is of the same order as the result found above for all the coasts. We have to realize, however, that the lengths are not sufficient to give much weight to this statistical figure. Still the result is such that a correlation of these "folding" coasts with the Net seems likely.

The supposition that for these coasts we may reduce the problem of the correlation with the Net to the question of how the correlation of the trends of crustal folding can be explained, is in harmony with the unmistakable correlation shown by the mountain formations for the continents. For Central Europe, we find the following examples: Hohe Venn and Sauerland; Eifel and Westerwald; Hunsrück and Taunus; Thüringer Wald; Erzgebirge; Sudeten; Böhmer Wald; Schwäbische Jura; Swiss Jura; and a great part of the Alps and the Carpathians. The number of ranges not in harmony with the Net is much smaller. We shall not further discuss this question, however, because here a deeper geological study is required, which the writer does not feel competent to undertake. We may state, nevertheless, that the general trends of the Caledonian and Variscian, as well as the Cenozoic folding in the whole of Europe, clearly seems to show a correlation with the two directions of the Net. This correlation of folding and shearing net is not surprising; as we shall further discuss in the next Chapter, we may expect the presence of shear planes through the crust to affect the trend of folding, and this circumstance may go far in explaining the curious twisted course of the folding axis in many parts of the great geosynclines.

Returning to the problem concerning the continental coast lines, we may conclude that, as far as these lines are determined by crustal folding, the problem may be reduced to the one mentioned above which seems easier to attack. The question may be put whether perhaps in this way a solution may also be obtained for the other coast lines, namely, by the hypothesis that these coasts have been determined in a similar way by earlier folding in old Pre-Cambrian periods. In the next Chapter we shall discuss this possibility and its consequences for the great problem of the origin of the continents. We shall likewise examine another possible explanation for the correlation of coast lines and shearing net.

Before leaving the subject of the evidence provided by the Earth's topography, we have to mention still another group of facts. Examining the map we may be struck by some cases where major topographic features coincide over great lengths with the same, or nearly the same, curve of the Net. It looks as if these curves represent the place where the Earth's crust has finally given way to the stresses after the stage of yielding and "hardening" had been past. If larger movements occur along the shear planes, we may expect them to continue over great distances, eventually from one area of slight deformation to another of these areas. Obviously it is not necessary that this occur over its entire length in exactly the same shear curve; it is clear that it may shift to a neighboring curve and so we must rather expect zones of deformation extending over large distances.

The following instances may be given; they have been marked on the map of Figure 10:

(1) The zone following the east coast of South America, the Sierra Leone Ridge, the northwest coast of Africa, the east coast of Spain, part of the Alps, the Schwäbische Jura, and the Bohemian mountains

(2) The zone following the Carlsberg Ridge, the Red Sea, the west coast of Italy, the south coast of France, the Pyrenees, the European shelf from Bayonne to west of Lands End, and the continuation towards the Mid-Atlantic Ridge

(3) The zone bordering the east coast of Asia

(4) The zone following the east coasts of Africa and Arabia, possibly continuing in the mountains of Baluchistan and Afghanistan towards the Hindu Kush; it may be that we can pursue this zone on the other side via the Cape Ridge, the Meteor Bank, and Bouvet Island towards the South Orkneys and Graham Land

(5) The zone probably beginning in the Chwanben, following the mountains of Burma, the Andaman and Nicobar Islands, Sumatra, and continuing in the west coast of Australia

(6) Possibly a zone from Formosa along the east coast of the Philippines, the west and east coasts of the western part of New Guinea, the northeast coast of Queensland, and the New Zealand Ridge towards New Zealand; it may be that the two last zones more or less find a continuation in the west coast of Victoria and Tasmania and in submarine formations towards Balleny Island and the Ross Sea

(7) A zone following the northeast coasts of the Bahamas and of South America, which may perhaps continue in the Rio Grande Ridge via Tristan da Cunha towards the Atlantic-Indian Ridge

(8) A zone following a great part of the west coast of North America and a part of the west coast of South America, which may perhaps be pursued in this Continent.

Although perhaps part of this material is illusive or caused by accidental coincidence, it does not seem likely that this is the case for all of it. As far as it is real it is a good illustration of the fact that the shearing of the crust does not in itself bring about the topography, but that other causes are responsible. Otherwise we should not find so many entirely different features in the same curve as is, for example, the case for the first two curves of the above list. In the next Chapter we shall discuss in detail how we can explain the origin of these different kinds of topography in harmony with the shearing net.

In closing the discussion of the evidence given by the topography, it may be remarked that no particular features have been found in the areas inside the stipoled lines where we may expect that the shearing planes are not normal to the crust. So no light on this part of the theory could be obtained.

We shall now briefly examine the evidence provided by the geophysical data. For the North Atlantic they confirm in two ways the hypothesis of a net of shear planes intersecting the crust. In the first place the numerous volcanic islands showing a linear distribution of the volcanoes point in this direction, and in the second place the gravity anomalies show that these islands, as well as the submarine ridges, are probably not formed by crustal folding or buckling but that a system of block-faulting is more likely here [VENING MEINESZ, 1942]. As has been mentioned before, these results as well as the preponderance of two main topographic trends over the whole region have led to the undertaking of this investigation. In general we may say that our hypothesis gives a satisfactory explanation of the volcanism at the Earth's surface as far as it does not accompany tectonic action in orogenic areas.

Another area where the gravity results give evidence for our subject is the East Indian Archipelago (see Fig. 11). As has been set forth elsewhere [VENING MEINESZ, 1934, 1940], the field of anomalies in this area shows narrow belts of large negative anomalies probably disclosing a downward buckling of the Earth's crust; the belt shows folding and overthrusting of the layers at the surface. It is likely, therefore, that in these belts the crust is subject to strong horizontal compression and the direction of the compression can be derived from the anomaly field; it has an azimuth of about 160° east of north. This direction coincides remarkably well with one of the two directions of the shearing net, and so we may well suppose that this compression is caused by a movement relative to its neighbors of the crustal block comprised between the fifth and the sixth zone of the above list. The Net thus explains the direction of this major crustal phenomenon. In the above-mentioned publications [VENING MEINESZ, 1934, 1940, and 1942], the writer assumed an originally unbroken crust and attributed this direction to the direction of the compressive force working on the crust, but, in view of the present explanation, this force might have worked in a somewhat different sense, although a great deviation does not seem likely.

A further correlation to the Net is shown by the eastern half of the anomaly field. The two belts of negative anomalies, over east Celebes and over Timor, as well as a belt between the weaker positive anomalies than the neighboring basins show, are all parallel to one of the two directions, while two other belts, one over the southeastern arm of Celebes and one over the islands of Ceram and Obi, coincide with the second. It is also clear that if the most northern of the two belts of strong negative anomalies, that is, that over east Celebes, really represents a great horizontal shortening of the crust, this can only be explained by a shearing of the crust that allowed the crustal blocks on both sides of the belt to approach each other, whereas the parts to the west did not undergo any relative movement. It appears that this shearing plane is parallel to the second Net direction and, following the southeastern arm of Celebes, runs towards the Mangkalihat Peninsula of Borneo. This second Net direction appears likewise to play a part in the southeastern part of the archipelago, namely, in the direction of the twist of the southern belt of negative anomalies over Soemba and in the part of that belt running from the Kai Islands towards Ceram.

The topography of the East Indies also shows a clear correlation. Only a few lines of it have been included in our statistical investigation. We may mention here the west coast of Sumatra and the island ridge parallel to it as well as the main mountain ridge of Sumatra, the Boekit Barisan, the Palawan Island ridge with a part of the North Borneo Shelf in its continuation, the ridge of shoals running from Panay towards British Borneo, the Soeloe Archipelago, the two ridges running south of Mindanao with the Mindanao Trough to the east of them, the Mangkalihat Peninsula of Borneo, a second outjutting of the Borneo Shelf to the south of it, the eastern and southeastern arms of Celebes with the Toekang Besi Islands and the ridge connecting the Tiger Islands with the south arm, the ridges and troughs in the northwestern part of the Banda Sea, the northern arm of Halmaheira with the island of Morotai, the northeastern and southern arms of Halmaheira, the ridge between Ceram and the Kai Islands, the Lucipara Islands ridge and numerous other ridges in the same area, the ridge from Wetar to Seroea, the ridge from Timor via the Tanimbar Islands to the Kai Islands, and lastly the Australian Shelf. A more detailed study of the gravity field and the topography over the East Indies in connection with the shearing net may be reserved for a future occasion.

A great part of the West Indian area has also been surveyed gravimetrically, and a narrow belt of strong negative anomalies has likewise been found there [HESS, 1938; VENING MEINESZ and WRIGHT, 1930; BROWN and HESS, 1933], but the results are less complete and the study has not yet been finished. It is not possible, therefore, to draw conclusions about the direction of the compression, but it looks as if the problem is more complicated than in the East Indies; probably at least two directions are present. It seems likely that the South American Continent had a relative movement with regard to the block of the Caribbean Sea towards the north-northeast, that is to say, that its direction more or less coincides with one of the two net directions, but apparently this block itself moved towards the east-northeast with regard to the North American block, and this direction shows no correlation with the Net.

The topography also shows less correlation than in the East Indies. The Bartlett Trough and the Anegada Passage give the impression of being shear lines, and the gravity results are in harmony with this view, but their directions do not agree with the Net. Perhaps we can account for these deviations by the fact that they are situated in an area where the stresses caused by the shift of the poles are less than half of the maximum stresses, and that the corresponding shearing directions are, therefore, less predominant here. There are, however, several topographic directions in harmony with the Net; we may mention the following: East coast of Yucatan and Honduras, a line which begins in a ridge connecting the Galapagos Islands with Central America and which continues in the east coast of Nicaragua, the last one marked by the small islands and banks of Albuquerque Cays, St. Andrews Island, Old Providence, Quito Sueño Bank, and Rosalind Bank, and which perhaps finds a continuation in the edge of the shelf to the east of the United States up to New York; further the line of shoals about 250 km to the east of the small islands mentioned which continues in Windward Passage and Caicos Passage and perhaps in the Bermudas; the shelf line of the South American coast from the Gulf of Darien to Cartagena, which continues in the Beata Ridge and the coast of Hispaniola from Punta Beata to Azua; the ridge of the Lesser Antilles from Grenada to St. Lucia, and the parallel ridges to the west and the east of it; the different passages in the eastern Bahamas as, for example, the Turks Island Passage and the Caicos Passage, the Bonaire and Los Roques Trenches; the northeastern edge of the Bahamas Shelf and the length direction of the sounds in that archipelago; the shelf edges of the eastern and western coasts of Cuba; a line of shoal places running southeast from the west coast of Jamaica; and a few smaller features. Several of these lines have already been noticed by SONDER [1936-38] in a paper on "lineament tectonics" in this area.

As no sufficiently complete and detailed gravimetric surveys have been made in other areas where tectonic orogeny is going on in the present period, no further data about the direction of horizontal compression of the Earth's crust have been obtained in this way which could be compared to the directions of the Net.

An instance of a gravimetric survey disclosing the structural lines of an area in great detail, and thus providing the possibility of checking the correlation with the Net, is furnished by the new anomaly map of the Netherlands. This map has been compiled from the observations of the "Bataafsche Petroleum My," the Netherlands Government Mines, and the Netherlands Geodetic Commission, all made with instruments belonging to the first mentioned company. The great number of observations rendered possible by the rapid determinations with modern gravimeters permitted representation of the gravity anomalies in great detail. The map shows a striking predominance of the southeast-northwest direction in all the detailed subterranean structures and thus proves a strong correlation to the corresponding Net direction. This direction was well known in the southeastern part of the country where the block faulting along fault planes in this sense had already been investigated by numerous borings and by mining; it has now been proved to continue over the whole country. The geological interpretation of this map will not be entered upon here. It is curious to see that earlier gravimetric maps of the Netherlands, which were much less detailed, barely indicated this direction [VENING MEINESZ, 1923]; only the greater detailing brought it forth.

Another field of gravity results showing a clear correlation with the two directions of Net 1 is found in the western part of the Mediterranean. This area has been surveyed by the well-known gravity expeditions of Cassinis and De Pisa in the Submarine *Vettore Pisani* of the Italian Navy, of Marti in the French Submarine *Fresnel*, and of Pélissier in the Submarine *Espoir*, likewise of the French Navy. The results have been studied by COSTER [1945], who subjected them to an isostatic reduction of the Airy-Heiskanen type and of the regional type, both for a crustal thickness, T, of 30 km. Examining several gravity profiles, Coster comes to the conclusion that nearly everywhere the isostatic compensation has a local, or nearly local, character, which points to an area here of block faulting. In connection with this result we reproduce in Figure 12 the map of the anomalies found by the local reduction. We see that the whole western and northern part of this map shows two prevailing directions, northwest and northeast, which coincide remarkably well with the two directions of Net 1. This is especially noteworthy as the topography in this area does not show this correlation so clearly, as already mentioned. The gravimetric map seems to show better the courses of the faults between the different crustal blocks than the topography. Only in the southeastern part of the map, that is, in the area of Sicily and Calabria, the coincidence with the directions of Net 1 is less pronounced. We may remark, however, that here the crustal deformation probably has more the character of the geosynclinal type, as is indicated, for example, by the strong seismic activity in this area, and so deviations from the Net are not surprising.

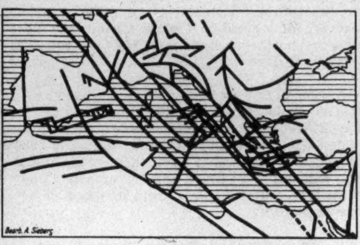


Fig. 13--Tectonic pattern of Mediterranean Region [after A. Sieberg]

Turning to the seismic evidence, we find nearly no deductions of positions of shear planes in earthquake centers that have a bearing on our problem. A number of these determinations have been made in Japan by Shida, Tanahasi, etc., but here the shear planes probably have their origin in tectonic phenomena; they do not coincide with the Net directions. One plane of shear corresponding to one of the two Net directions, along which movement is still going on, is well known, namely, the San Andreas Fault in California, which brought about the earthquake catastrophe of San Francisco; it is the longest fault plane observed on Earth. No determination of its position with regard to the vertical is known, however, to the writer. So, as yet, no conclusions from such determinations can be drawn about the slope of the shear planes of our Net with regard to the vertical. It is to be hoped that in the future data about this point will become available.

The other way in which seismic results may shed light on our problem, the deduction based on the situation of the earthquake centers and on the geological data of the planes along which the movement has been going on, has been especially taken up by Sieberg [see also HOBBS-RUSKA, 1910]. As the geology plays, however, a part in these interpretations, and as we shall refrain from discussing data from that side, we shall not consider this material; for this subject the reader may be referred to the publications of Sieberg [for example, his "Erdbebengeographie" in Gutenberg's "Handbuch der Geophysik," v. 4, 1932]. We shall only reproduce in Figure 13 the map Sieberg gives on page 769 of this comprehensive summary of the subject. Especially the southeast-northwest direction is clearly shown; the other appears in the east of Spain and in the eastern Mediterranean. Other instances of good correspondence may be found in the map [p. 710] for the western and northern parts of France, in the map [p. 719] of Central Europe, in many lines of the map of the Rhineland [p. 721], in the maps of Italy [p. 746], and of Corsica and Sardinia [p. 771], in the map of the Aegean Sea [p. 777], in that of China [p. 828], in those of South Africa [p. 892 and 897], in that of California [p. 942], and in fact in the majority of the maps of this publication.

Before leaving the subject of the correlation of geophysical phenomena and the shearing net of the Earth's crust we may briefly mention the curious relation to the Earth's magnetism pointed out by S. W. VISSER [1943]. In the first place the magnetic equator nearly coincides with the great circle where the critical stress is a maximum; this circle passes through the points where this stress has its maximum value indicated by 1.00 in Net 1, and from there it follows the diagonals of the Net compartments. In the second place the residual field after deducting uniform magnetization shows regional positive and negative areas more or less coinciding with the areas of minimum stress in Net 1 and with areas halfway between them. It is difficult to decide whether these coincidences are fortuitous. There is no doubt that further investigations of possible connections between the two phenomena would be worth-while.

As has been mentioned in the beginning of this Chapter, geologists such as Sederholm, Hobbs, Sonder, and others have found geologic and geomorphologic evidence in favor of the idea that a world-wide system of shear planes exists in the Earth's crust. They obtained indications of a few predominant directions, of which northwest and northeast are the most common, and they called these directions "lineaments." On page 225 of his comprehensive paper on this subject in the Eclogae Helvetiae SONDER [1938] gave a nomenclature in which he defined the word "lineament" as the prevailing direction in an area, whereas he proposes the word "linear" for a special plane in this sense and the word "zonale" as a narrow zone of such planes continuing over great distance (see, for example, Fig. 10). In this paper Sonder remarks that a northwest and northeast direction can not be predominant over the whole Earth's surface, because in that case the shear curves should have to be loxodromic and this does not appear likely; for the polar areas, for example, it would lead to absurd consequences. He concludes, therefore, that it can not be more than a rough approximation and he finds, in fact, somewhat different directions for different areas. From the viewpoint of our hypothesis this becomes clear; for a great part of the inhabited regions of our Globe Net 1 shows, roughly speaking, northwest and northeast directions, but they differ for different areas and for the polar regions they are entirely different.

In this same paper Sonder deals also with the question as to what period these shear planes can have originated, and he expresses the opinion that they must be very old; he thus came to the same conclusion as the writer, and the fact that the continental coasts seem to show a correlation does not indeed appear to admit any other view. Sonder also points out that the fact of fairly recent sedimentary layers showing the effect of the shearing does not mean that these shear planes must be younger than the sediments; it only proves, in fact, that in recent times new movements along these planes must have taken place. It is clear that all forces working on a crust intersected by shear planes are indeed likely to give rise to such movements.

SONDER [1938, p. 212] attacks the problem of how the existence of shearing planes in the crust can bring about the topography which at the Earth's surface seems to accompany their presence. We shall examine this question in detail in the next Chapter, where we shall mention Sonder's valuable contributions to the problem. In this Chapter we shall deal with the evidence given by him and other "lineament" geologists for the presence of shearing planes in the crust.

One of the Continents where this evidence is clearest is Africa. KRENKEL'S map [1925], reproduced in Figure 14, as well as the one given by SONDER [1938, p. 208] clearly show two systems of lines which nearly coincide with the two directions of our Net. We may also reproduce here a chart of the Gulf of Aden (see Fig. 15) which has been compiled by TH. STOCKS [1941] from recent maps and soundings. It shows a series of ridges and troughs fitting perfectly in the general picture, their direction coinciding exactly with one of the two Net directions; the area of this map has been included in the measurement of the Indian Ocean. The two African directions are also evident in KRENKEL'S map [1922] of the Graben zones in east Africa. It seems probable that this whole last area has been subject to tension in an approximately east-west sense and that it, therefore, has a length direction in a more or less north-south sense, but the great majority of the faulting occurred in two directions about coinciding with those of the Net. It may be that the east-west tension itself has been caused by the shift of the poles--the Formulas (13) of Chapter II, in fact, indicate tension in this sense here--but as the Graben formations are much younger than we supposed for the polar shift, it seems more likely that other forces are responsible for it.

The good correspondence of practically the whole African Continent with our shearing net adds 29.8 million km^2 to the part of the Earth's surface showing a correlation to the Net. It thus brings the figure of page 35 up to 279.4 million km^2.

For Europe there is also a great deal of evidence. The earliest investigations of this kind have been made by DAUBRÉE [1880]; they show, for example, a northwest lineament in the watercourses of northwestern France [SONDER, 1938, p. 201]. For Scandinavia and Finland SEDERHOLM [1913] has collected extensive material, of which we reproduce the map of the Päijänne See in Finland, which shows unmistakable evidence of faults in a northwest direction (see Fig. 16), and the map representing the watercourses and fault lines in the whole of Fennoskandia (see Fig. 17). This map shows a strongly predominant northwest lineament over nearly the entire area, and this corresponds to one of the two directions of the Net. The second direction is less generally represented,

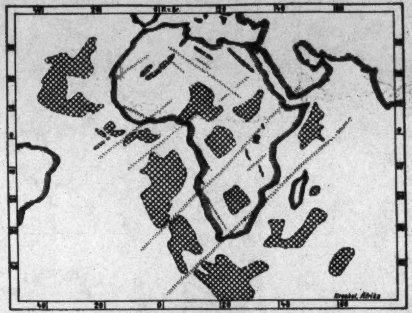
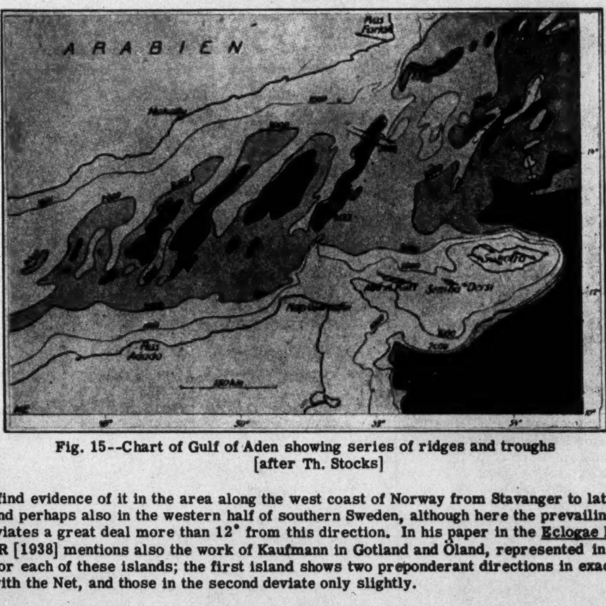


Fig. 14--Tectonic patterns for Africa and neighboring oceanic basins [after E. Krenkel]



γ

Fig. 15--Chart of Gulf of Aden showing series of ridges and troughs [after Th. Stocks]

but we find evidence of it in the area along the west coast of Norway from Stavanger to latitude 66° north and perhaps also in the western half of southern Sweden, although here the prevailing direction deviates a great deal more than 12° from this direction. In his paper in the Eclogae Helvetiae SONDER [1938] mentions also the work of Kaufmann in Gotland and Öland, represented in fault roses for each of these islands; the first island shows two preponderant directions in exact harmony with the Net, and those in the second deviate only slightly.

An interesting example is also given by SONDER [1938, p. 207] in a map of the upper Rhine Graben (see Fig. 18), which shows that the smaller faults on both sides of the Graben are in better harmony with the northeast direction of our Net than the main direction of the Graben itself. It appears that these smaller faults may be attributed to the original polar shift and it is reasonable to assume that the Graben formed by other more recent causes has only partially

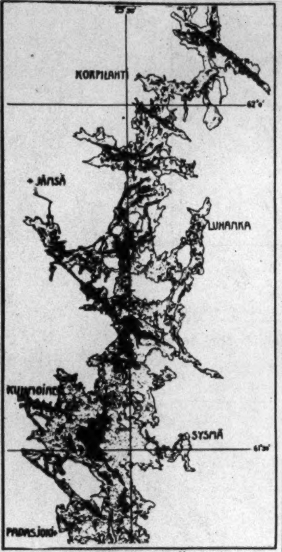

KORPILAHTI
62°0'
JÄMSÄ
LUHANKA
KUHMOINEN
SYSMÄ
61°30'
PADASJOKI

Fig. 16--Map of Päyänne Lake, Finland, showing fault pattern [after Sederholm]

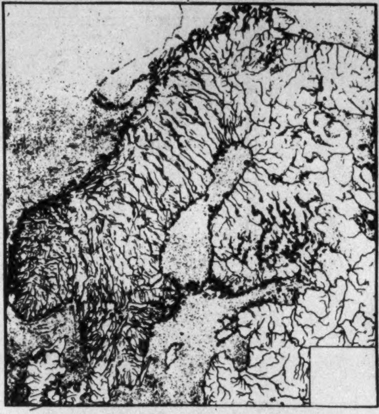
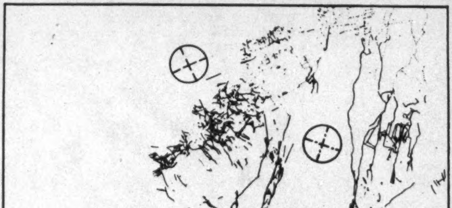


Fig. 17--Water courses and fault lines of Fennoskandia [after Sederholm]

Fig. 18--Fault patterns of upper Rhine Graben [after Cloos, modified by Sonder] ⟶


afrikanisch
asiatisch
atlantisch
30km

followed the old faults. The fault roses added by Sonder show the differences in the directions attributed by him to different areas.

SONDER [1938, p. 219] gives a map of the Aegean in which he traces two predominant directions practically coinciding with those of our Net and each occurring in many lines; this interpretation agrees with that given by Sieberg as mentioned above; the northwest direction, moreover, is also preponderant in many structural lines of the Balkans.

In all these European areas the directions are in harmony with our Net. If we add to this the clear geophysical evidence for the Netherlands and the well-known faults of Scotland, which are likewise in agreement with it, we may conclude that as far as it goes the evidence for Europe supports our hypothesis; the above-mentioned correlation of the topography in Central Europe and in the Mediterranean Area are further assets. It may be hoped that in the future more geological checking will be forthcoming.

For the North American Continent material has been collected by HOBBS [1911], who was one of the first geologists giving his attention to the problem of fracture nets, and who has given a valuable summary of instances. The North American examples do not agree in quite the same measure with our Net as those in Africa and Europe, although in several cases at least one direction, and sometimes both directions, coincide; in one of the clearest cases of lineaments--in Western Ontario near Timiskaming Lake--both directions, for example, are well in harmony with it (see Fig. 19). A lesser agreement is not surprising in this Continent, because in a great part of it the stresses caused by the shift of the poles are so small that no shearing effect can be expected. In those areas other forces working on the Earth's crust do not find prepared fault planes, and so shear must occur in directions connected with these forces, while, in areas where the polar shift has brought about shearing, the effect of later forces will in many cases occur along the older planes. Since in the northwestern part of North America the shift of the pole must have given rise to greater stress, we may here expect a stronger correlation with our Net and the two examples of lineaments mentioned by SEDERHOLM [1913, pp. 25ff] in this area, the fault valleys near San Francisco and the area of Jakutat Bay in Alaska give indeed coinciding directions. Figure 20 represents the latter of the two, where both directions of the Net can be recognized--the north-northwest direction among others for the coast line of Jakutat Bay and in Russell Fjord and the west direction in Nunatak Fjord and in other lines.

[In September 1946, after the preceding paragraphs were written, the author had a discussion with J. T. Wilson of the University of Toronto about an extensive study he is making of the trend-lines in the Canadian Shield, mostly using the topographic indications shown by air maps and other topographic maps. Where possible he has compared his conclusions with the geological data and has found them everywhere confirmed. The results of his investigations give a striking corroboration of Net 1. In the whole area east of the meridian of 90° west, also comprising the major part of Labrador, the correlation is about 95 per cent, and in the area west of this meridian extending to the areas around Great Slave Lake and Great Bear Lake it is 60 to 70 per cent. These results cover nearly the entire northern part of the North American continent east of the Rocky Mountains.]

For the other continents not much is known. For the southern part of South America, WINDHAUSEN [1918] has indicated a system of two fracture directions (see Fig. 21) of which the northwest direction coincides with the corresponding direction of our Net, whereas the second slightly deviates, but for the rest of this Continent no data are known to the writer. The same is true for Australia, while for Asia only a few short remarks are given by SONDER in the Eclogae Helvetiae of 1938; on page 205 he mentions that AHNERT [1926] has found a northeast orientation and smaller northwest fractures in Eastern Asia and that Tongking shows a northwest lineament, and on page 206 northwest and northeast orientations for the western border of Asia. All these directions seem to be in harmony with our Net, but more details are required before we can attribute weight to this agreement.

We may conclude that the material hitherto collected by the lineament tectonicians gives positive evidence in favor of our hypothesis in Europe and in Africa and a little elsewhere. Contrary evidence has not yet been obtained. It is true that also north-south and east-west lineaments have been mentioned, but these directions are less frequent and their number is not sufficient to permit the conclusion that they occur systematically over a great part of the Earth's surface. In the suboceanic topography, moreover, no evidence for these directions has been found. As far as can now be decided, these directions may be fortuitous and may be caused by forces of a regional character; there is no need yet to look for another planetary effect that could explain them.

The result of our investigation in this Chapter is that the evidence collected over more than half of the Earth's surface is decidedly in favor of our hypothesis. It does not seem likely that

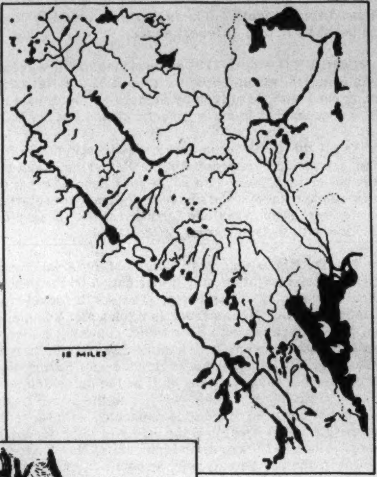


Fig. 19--Drainage map, part of District of Nipissing [after W. H. Hobbs] ⟶

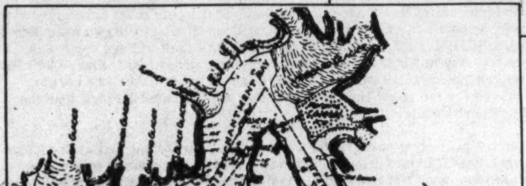

DISENCHANTMENT BAY
Nunatak Fiord
Russell Fiord
YAKUTAT BAY
YAKUTAT

Fig. 20--Jakutat Bay, Alaska ⟵ [after Tarr and Martin]

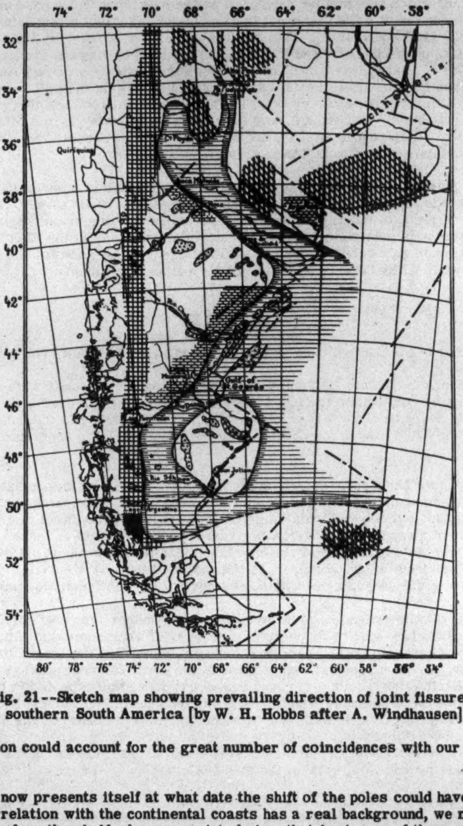


Fig. 21--Sketch map showing prevailing direction of joint fissures, southern South America [by W. H. Hobbs after A. Windhausen]

another phenomenon could account for the great number of coincidences with our Net that have been found.

The question now presents itself at what date the shift of the poles could have taken place. If we admit that the correlation with the continental coasts has a real background, we must suppose it to have taken place before the shelf edges came into being, that is, in one of the earliest periods of the crust's history. If we should neglect this coastal evidence, we should still have to assume it to be old; the correlation of our Net with the trend of the variscian orogeny would compel us to suppose it at least Pre-Carboniferous. As there is hardly reason, however, to put aside the coastal correlation, we may consider a much older date as probable.

This result has an important bearing on geophysical theories. As the net of shearing brought about by the polar shift can only have originated in a closed rigid shell over the whole Earth's surface, every hypothesis assuming horizontal displacements of the continents over great distances in periods previous to the shearing would have to be abandoned. This is likewise inevitable because of the fact that such displacements must have so much disturbed the net of fault planes, that the correlation would have disappeared over large parts of the Earth's surface. We may conclude that Wegener's well-known theory is not compatible with the hypothesis advocated in this paper.

We may draw two more conclusions from our results. In the first place they confirm the picture of a rigid crust floating on a plastic substratum, a picture first introduced by Airy to explain isostasy, and which was further supported by the extension to the case of regional isostatic compensation on the basis of a floating crust bending under the effect of superimposed loads [VENING MEINESZ, 1939 and 1941 a]. This picture was also confirmed by the studies of RUSSELL [1939] on the Mississippi Delta, of VENING MEINESZ [1941 b] on Hawaii, etc., and of SAURAMO [1939] on "the mode of land upheaval in Fennoscandia during late-Quaternary time." It is likewise in harmony with the theory of crustal buckling given to explain the belts of negative anomalies in the East and West Indies [see Chapter IV]. The hypothesis dealt with in this paper gives it a further support. This purely mechanical view of the crust's behavior is no doubt not complete; it is to be expected that other phenomena, as, for example, chemical processes, differentiation, and metamorphism, also have played a part in the history of the crust.

In the second place it is interesting to notice that the evidence in favor of our Net of fault planes gives support to the idea that we may apply the hypothesis of BYLAARD [1935, 1936], further elaborated by Van Iterson, to the case of deformations in the Earth's crust. Bylaard himself has already affirmed this in papers concerning the crustal deformations in the East Indies. A more thorough investigation of this question, which seems of great importance for the geophysics of the Earth's crust, is worth while. It may be reserved for a future occasion.

CHAPTER IV

The Effect on the Topography of Fault Planes in the Crust

The main evidence in Chapter III favorable to the existence of a world-wide shearing net in the Earth's crust is the correlation the topography shows with our Net over a great part of the Earth's surface. In order to make this evidence valid, it is necessary to indicate how the presence of shear planes in the crust may bring about topographic features--the problem investigated in this Chapter.

For this purpose we shall successively study the effect of volcanism, isostatic effects, vertical or epirogenic movements, the effect of horizontal stresses in the crust, orogenic deformations such as buckling, folding, and overthrusting of the crust and its layers, the effect of erosion, and the effect on the course of rivers and smaller water courses. For several of these agents new viewpoints will arise from the supposition of pre-existing shear planes in the crust; this will be especially the case for the orogenic phenomena. At the end of Chapter IV we shall discuss the problem of how a correlation of the shearing net with the borders of the continents can perhaps be explained.

Before starting this investigation we have first to see whether the origin of these shear planes itself already can have given rise to topographic features. If we assume that the shearing of the crust occurred through plastic flow in narrow zones so situated that the length dimensions of these zones do not change, the dimensions at right angles to the crust can not remain unaltered, and so movements of the Earth's surface in a vertical sense may indeed be expected in these zones. We shall try to determine the topography which in this way may come into being. For doing this we first derive the component of the deformation at right angles to the crust on the supposition that the whole crust has been subject to plastic flow under the effect of the stresses given by Formulas (13) of Chapter II. The shortening, ϵ, in the crust of a unit of length of the normal to the crust's surface in the case of plastic flow, that is, for $m = 2$ is given by

$$\epsilon = (\sigma_\delta + \sigma_\alpha)/2E = [2m/(5m+1)]\beta \sin\theta \sin^2\delta \sin(2\alpha - \theta) \qquad (49)$$

Assuming that the part of the crust considered has not yet reached isostatic equilibrium, the rising at the surface would be $\delta h = -(1/2)T\epsilon$, in which T is the thickness of the rigid crust. If, on the contrary, the readjustment has taken place, we find for the usual assumptions of 2.67 and 3.27 for the densities of the crust and of the plastic substratum $\delta h = -0.1835T\epsilon$.

Returning to the hypothesis that flowing occurs only in narrow strips of the crust, and assuming that these strips represent a part of the Earth's surface denoted by the small quantity μ, we find that if in the remaining part of the crust the stress entirely disappears, the whole deformation is concentrated in the strips and that, therefore, their rising with regard to the other parts of the crust is given by (50).

$$\delta h = -0.1835T\epsilon/\mu \qquad (50)$$

If the stress does not entirely disappear in the remaining parts of the crust, the value of δh is correspondingly smaller.

In Formula (49) we have to introduce the value of m for elastic deformation because the stress distribution in the Earth's crust is practically determined by the elastic stresses and so we shall put $m = 4.1$; the first factor of Formula (50), moreover, does not vary much for another value of m. Introducing $\beta = (1/297)$, $\theta = 70°$, $T = 30$ km, and a rather arbitrarily chosen ratio $\mu = (1/20)$ we obtain for isostatic readjustment

$$\delta h = -133 \sin^2 \delta \sin(2\alpha - \theta) \text{ meter} \quad \ldots\ldots\ldots\ldots\ldots \quad (51A)$$

and in case isostasy has not been established

$$\delta h = -362 \sin^2 \delta \sin(2\alpha - \theta) \text{ meter} \quad \ldots\ldots\ldots\ldots\ldots \quad (51B)$$

So we see that the elevation or depression, thus coming into being in the deformed strips, is small; in the more probable case that the isostatic equilibrium has been readjusted, it varies over the Earth's surface between + 133m and - 133m. The map of Figure 22 shows the value of minus the variable factor of Formula (51), which has to be multiplied by 133m or 362m to get the rising of the Earth's surface in the strips.

It is hardly probable that remnants of such features are still present. It is hardly necessary to say this seems out of the question on land where, if they have indeed existed, erosion must have worn them off or sedimentation filled them long ago, but in submerged areas it also seems unlikely, because since those very early periods, in which we assume the shearing to have taken place, we must expect considerable sedimentation, even in the deep oceans, and so probably all evidence must have been hidden. The cross sections of the ridges or depressions which might have been brought about are not easy to predict; we can only say that the area of the cross sections must have corresponded to the product of the elevation δh by the horizontal dimension of which the mean value in a certain area is given by the ratio μ. As the course of the strip, however, under the effect of irregularities in the physical properties of the crust must no doubt deviate from the straight course, and as the relative movement of the crustal parts on both sides of the strip must have had a component parallel to its general direction, the horizontal dimensions of the ridges and depressions must have varied accordingly.

We shall now proceed to examine other effects that may have brought about changes in topography. Some of these effects must have acted as a direct consequence of the shearing, whereas others, as, for example, the orogenic phenomena, may have occurred long afterwards, but as these last occurrences must have been altered by the presence of the shearing planes in the crust, they must also have given rise to a topography correlated to our Net. We shall begin with the more directly connected phenomena; in many cases, however, later effects may be mixed up with them.

In the first and most important place we may mention the volcanism which the shearing of the crust must have brought about. It is clear that even if this shearing has taken place in the shape of plastic flow in a thin layer along a narrow belt of the crust, it must have released plutonic action in this layer, which in many cases must have come to the Earth's surface. This plutonic and volcanic activity must no doubt in many areas have continued up to the present time, as other forces working in the crust must have made the shear planes alive again and thus have reopened the magma passages. The distribution of the volcanoes over the Earth is well in harmony with our supposition. It has been generally recognized that the volcanoes may be brought under two headings, those occurring in orogenic belts and those situated elsewhere. The first, usually called of the "Pacific" type, are characterized by calc-alkaline magmas, while the others of the "Atlantic" type develop alkaline effusives [KENNEDY and ANDERSON, 1938]. We must expect the shear planes of our Net to produce the latter type, and this seems indeed to be true. These latter volcanoes often occur in straight rows, for example, in several oceanic islands, as Pico with Fayal, San Jorge and San Miguel in the Azores, and this has been explained, no doubt rightly, by the supposition that they are caused by fault planes in the crust. As far as the writer knows these rows are all in harmony with the Net, and as for the other volcanoes of this type, they are often accompanied by topographical features, as, for example, submarine banks, in line with the volcanoes, the directions of which likewise coincide with the Net. For the volcanoes of the calc-alkaline type this is not so generally true, although there are many instances of good concurrence. It is clear that this can be explained by the fact that these volcanoes occur in orogenic belts, and that the strain in the crust during the great tectonical phenomena in some cases may have been relieved by shear along the planes of our Net, but in others must have formed new fault planes in other directions.

Another point in favor of our hypothesis is that the volcanoes of the alkaline type occur especially in those areas where the stresses, as our map indicates, are larger than three-quarters of the maximum value, and where the movement along the shear planes must have been correspondingly great. This is striking for the Atlantic, where, for example, the situation of Iceland in the narrow zone of strong stress is noteworthy. Only the Bermudas, which probably also have a volcanic origin, are situated outside. It is likewise true for the Pacific, where only a few islands, namely, Easter Island, Sala y Gomez, Juan Fernandez, and the Galapagos Islands, are situated in the southeastern part, in an area of smaller stress. It is not certain, however, whether the volcanoes of these islands indeed belong to the normal alkaline type; they do not produce nepheline-bearing effusives, and they are not grouped in linear rows, as are nearly all the other Pacific islands east of the andesite line. The volcanic islands of the western Indian Ocean seem also to form an exception, but here again it is doubtful whether these islands belong to the alkaline group; some of them may perhaps be connected with tectonic phenomena, and the curved shape of the ridges seems to point in this direction. The Seychelles, moreover, show granites and syenites, Réunion feldspar basalt, gabbro and peridotite, and Mauritius a basement of diorite and schist, and so the ridge connecting these islands does not seem to belong to the alkaline type. The same is probably true for the Kerguelen Islands, where especially plagioclase basalt occurs.

The fact that thus a great part, if not all, of the Earth's volcanism in non-orogenic areas may be accounted for by our hypothesis appears to give it a valuable support.

We must expect that the topographic features caused by the volcanic action along the fault planes of our Net must be rather irregular. The unevenness of these planes in connection with the relative movement of the crustal blocks on both sides with regard to each other must have brought about fissures, or at least decrease of pressure, at irregular intervals in these planes, and so the volcanic outbursts must have varied considerably in these zones. We may expect, therefore, that the ridges thus originating must have a greatly varying height and breadth, and that they may even be entirely interrupted in some parts. This is in good harmony with many of the ridges in the Atlantic and Pacific Oceans, as far as we can judge from the charts derived from the many recent sonic soundings. Instances of these irregularities may be found in the ridge connecting the Gorringe Bank with the Portuguese Coast, the ridge running southwest from the islands of Fayal and Pico, the ridge connecting Terceira and Graciosa, the ridge running southwest from the Josephine Bank, the ridges of the Sandwich Islands, and many others. As other topographic formations attending the planes of shear in the crust must be more regular, it seems probable that the greatest part of the submarine topography correlated to our Net in these oceans has come into being by volcanic action.

The irregularities in the fault planes mentioned above must no doubt also bring about volcanic outbursts, which are possible not only if there is no component of the relative movement of the crustal blocks away from each other, but also in those areas where this movement has a component towards each other. This is the case for the areas of positive values in the map of Figure 22. We may, however, expect a smaller number of volcanoes in these areas than elsewhere, and this is confirmed by the facts. This may explain the scarcity of volcanoes in the Arctic and Antarctic regions.

In Chapter III we have drawn attention to the viewpoint that the great number of shear planes in the crust may be explained by an analogy to the experiments with steel strips subjected to tension above the elastic limit. In these experiments, after a first zone of flowage has come into being, hardening intervenes and the deformations do not continue in this zone. A second zone forms and in its turn stops deforming, and this goes on until nearly the whole strip is interlarded by zones of flowing. If the tension further increases, breaking sets in at last in one of these zones. After shear has begun to occur in the crust, magma must rise at once, and it seems probable that the cleavage may thus be sealed up and continuation of the shearing prevented. A second plane of shear must then be formed, and so we see an analogous process to the hardening of the steel taking place in the crust, but on an infinitely bigger scale. In this way the formation of a great number of shear planes in the Earth's crust can be explained which otherwise seems difficult to understand. The process may no doubt continue up to the present time; forces working in the crust must still give rise to movements along the planes of weakness, but at any moment magma intrusions from below, eventually leading to volcanic outbursts at the surface, may increase the resistance in this zone and thus give rise to the stopping of the movement and possibly to the coming into action of other zones of weakness.

The question may be put what anomalies of gravity we may expect to find over volcanic topography caused by the presence of shear planes in the crust. If we assume that the fissures of the crust have been completely sealed by the magmatic material and that the crust acts, therefore, as an unbroken elastic plate, we can consider the volcanic topography as an excess of matter superimposed on this plate and causing it to bend. The result is that the isostatic compensation must be distributed according to the hypothesis of regional compensation [VENING MEINESZ, 1939, 1941 a], that is, in broad flat roots formed by this bending at the crustal boundaries where the density shows

a sudden increase. So we may expect that the anomalies will more or less disappear by regional isostatic reduction. The gravity results found over the Hawaiian Archipelago, over Madeira [VENING MEINESZ, 1941 b], over the Bermudas, and over St. Vincent (Cape Verde Islands) confirm this supposition; in general the radii of 174.3 km or 232.4 km give the most satisfactory results. The anomalies over the Azores Area and over some of the submarine banks of the North Atlantic, such as the Josephine Bank, show more irregular figures [VENING MEINESZ, 1942]; for some of the gravity profiles the regional isostatic reduction with varying radii provide the smallest anomalies, whereas for others in the same areas the local reduction meets the requirements better. The explanation seems easy; probably some of the shear planes in these areas have not been sealed and so the crust must react as a mosaic of crustal blocks carrying the volcanic loads and partially bending down and partially sinking in locally under their effect [VENING MEINESZ, 1942].

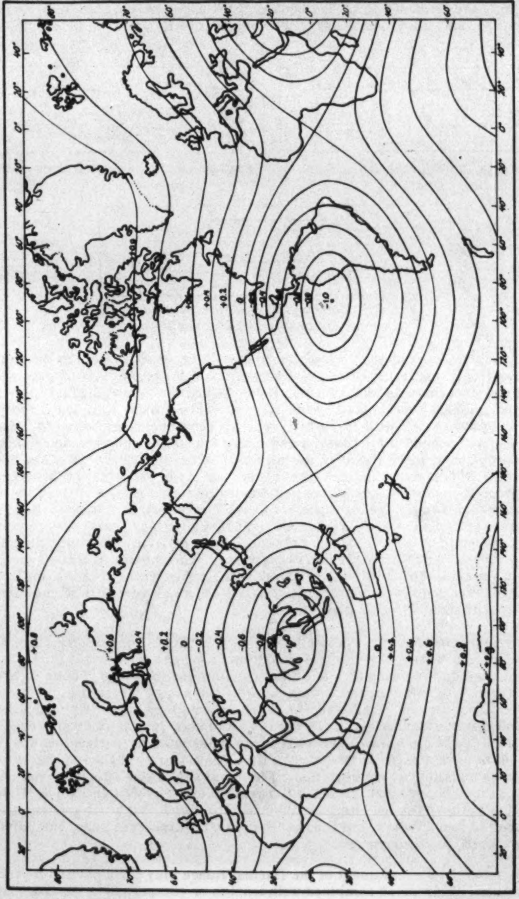


Fig. 22--World map of values of $(\sigma_\delta + \sigma_\alpha)$

A more detailed study of these questions and problems will appear in "Gravity expeditions at sea," v. 4 (to be published soon by Ned. Geod. Com.)]. Thus the gravity results found in the North Atlantic are in good harmony with our hypothesis of a system of shear planes and a volcanic topography superimposed on the crust.

As already mentioned the volcanism brought about by the shearing of the crust is probably the main cause of the topographic features correlated with the shearing net. We shall now proceed to other possible effects. In the first place we can affirm that shear planes not normal to the crust must lead to isostatic adjustments of the kind STEPHEN TABER [1927] first noted, at least if tension in the crust provides room for these crustal movements. As Figure 23 shows, two fault planes converging downwards must lead to the formation of a Graben, whereas diverging planes must bring about a ridge. In the same way parallel planes must give block tilting (see Fig. 24) and one plane a fault escarpment. If, on the contrary, the crust is subjected to a horizontal compression, the reverse must come into being; the formations to be expected in this case are represented in Figure 25.

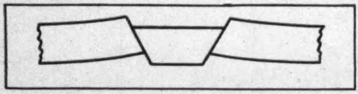


Fig. 23--Converging fault planes under tension producing a Graben

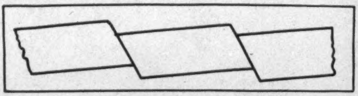


Fig. 24--Parallel fault planes under tension producing block faulting

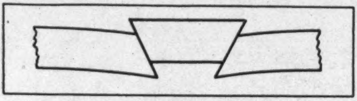


Fig. 25--Converging fault planes under compression producing a horst

If the shear planes formed by the shift of the poles concur exactly with the theoretical deductions, planes at relatively small distances from each other must practically be parallel, and so only block tilting and escarpments would form. These formations would then be limited to the areas of tilted shear planes, as indicated by the stippled curves in our Net, while the areas of vertical planes would have undergone no change. The process may be expected to have started at once after the shear had occurred for those areas where tension or compression was brought about in the crust in a direction at right angles to the direction of the plane. These areas may be derived from Figure 22, which shows the relative intensity of these stresses; in this Figure the positive sign corresponds to compression and the negative to tension. The forming of these escarpments must have continued in all areas, however, where a tensional or compressional stress has been working since. An instance of a formation of this last type may perhaps be found in the sinking away of the coast ranges of the Andes, which between Payta and Arica follow the directions of our Net. In this same direction STEINMANN [1929] supposes a continuation of these ranges to the northwest of Payta which would likewise have foundered. In this whole area the shift of the poles must have caused tension, but as the sinking must have been more recent it seems more likely that it has been brought about by other phenomena.

We have hitherto assumed that the position of the shear planes corresponded exactly to our deductions. It is clear, however, that the irregularities in the crust may well cause deviations, and so we need not exclude the possibility of other positions and of converging or diverging planes at short distances from each other, even if we adhere to our Net as far as the directions in the plane of the crust are concerned. Fairly recent crustal formations caused by such shear planes may perhaps be found in the East African rift valleys and in the coastal strip of Western Australia. The first are situated in the area where the shift of the poles must have given tension, and so these formations might even have started at that early date. The majority of these rifts follow the directions of our Net or do so with a slight deviation. Views vary about the question whether they are caused by tension or by compression. The gravity results found by BULLARD [1936] in his important investigation of this area led him to suppose compression, but most geologists still favor tension. As Figures 23 and 25 show, the shear planes must, in the first case, have diverged downwards and, in the second, have converged.

In Western Australia the escarpment of the Darling Range may perhaps also be attributed to the existence of a tilted shear plane combined with tension or compression. It must have been recently formed by the sinking of the coastal strip to the west of it. Probably the process is still active in the present period. As the writer had the occasion to investigate, the gravity field shows a curious deviation near Perth; he found strong negative anomalies over the coastal strip. [A discussion of these anomalies will soon appear in the publication above mentioned.]

The instances of topographic features mentioned above have all originated, no doubt, in much more recent periods than that in which we supposed the shift of the poles to have taken place. It is difficult to say whether there are still features present formed by the crustal catastrophe itself. For the effects we shall further discuss--the epirogenic and tectonic phenomena and erosion--this possibility does not exist; they are based on other forces working on the crust after the shear planes had come into being.

For the first, no long discussion is necessary. It is clear that epirogenic, or in general vertical forces exerted by the substratum and varying in horizontal sense, must give different displacements to crustal blocks separated by shear planes, and so escarpments along the lines where these planes reach the surface must in many cases have come into being. It will be difficult to recognize these formations in the submarine topography, but for the land topography we may perhaps be able to identify them, although even in this case it will not always be easy to distinguish between epirogenic causes and the effects of tension or compression in the crust as dealt with above. The few examples given for these last effects may likewise have been brought about, of course, by vertical forces exerted by the substratum.

The second cause of topography correlated to our Net--the effect of tectonic phenomena--will require a longer discussion. We shall base it on the hypothesis made in consequence of the finding of narrow belts of negative gravity anomalies in the East and West Indies, according to which, in the zones of tectonic folding and overthrusting of the surface layers, the major part of the crust is thrust downwards in the substratum in the form of a narrow root. This hypothesis suggested by the writer [VENING MEINESZ, 1930] has since found more and more support. We may mention here the investigation of the geology of the East Indies by Umbgrove, who found the supposition confirmed that these belts coincide with the areas of strong lateral compression of the surface layers [VENING MEINESZ, UMBGROVE, and KUENEN, 1934]. Special mention may likewise be made of the experiments of KUENEN [1936] with a layer of wax and paraffin floating on water and horizontally compressed; the layer, after a critical limit of the compressive force had been reached, began to show waves, and after some time one of the lower waves started pushing farther downwards and a local root came into being. These results proved to be in harmony with the theoretical treatment of the problem which shows that the phenomenon may probably be best understood as a kind of buckling of the floating crust after a critical stress has been exceeded [VENING MEINESZ, UMBGROVE, and KUENEN, 1934, pp. 44 ff and 117 ff; VENING MEINESZ, 1940]. Further support of the hypothesis was given by the following conclusions of others: By BUCHER [1933, p. 210] made on other grounds, which also suppose the origin of crustal roots in orogenic areas; by the study of KENNEDY and ANDERSON [1938, pp. 24-82] on "Crustal layers and the origin of magmas," in which they show that the volcanism in orogenic belts can not be understood without assuming the thickening in those belts of the crustal layers; by the studies of BYERLY [1938] on the Sierra Nevada, where he shows how the seismic results in California confirm "the great depth of penetration of the mountain mass" relative to the crust in the neighboring areas; by the interpretation by HESS [1938, pp. 71-96] of the gravity anomalies in the West Indies, where also a narrow belt of negative anomalies was found; by the study on mountain building by GRIGGS [1939], who made experiments on the formation of crustal roots by the action on the crust of subcrustal currents descending under the orogenic belt; and by the investigations and papers of many other writers.

Starting from the crustal-buckling hypothesis we shall first examine the theoretical problem of how the buckling process is affected by the presence of a fault plane. We must assume that at this place the crust can not resist bending in the same way as elsewhere, and in this connection we shall start from the assumption that no such resistance is at all present. This means that in a strip of the crust crossing the fault plane at right angles a hinge occurs at the point of intersection, or, in other words, that the momentum M of the stresses in a cross-section of this strip taken with regard to the horizontal middle line of the section is zero for a cross section through the fault plane.

Simplifying our problem by neglecting the Earth's curvature we have to derive the deformations of a floating plate of constant thickness T and infinite dimensions divided into two parts by a hinge line and subject to compression in a direction at right angles to the hinge line. It thus becomes a two-dimensional problem. Following the same line of solution as in an earlier paper [VENING MEINESZ, 1940, p. 285] we shall choose the X axis in the plane of the plate and the Y axis vertically downwards with the origin of the coordinates in the hinge point. Assuming that the deformations of the plate are small enough to allow neglecting of the second and higher powers of (dy/dx) and introducing the quantities

$$\ell_1 = \sqrt[4]{m^2ET^3/12(m^2 - 1)\theta_1 g} \qquad (52)$$

and

$$D_o = 2\theta_1 g \ell_1^2 \qquad (53)$$

where θ_1 is the specific density of the substratum, we obtain differential equation (54) for the displacement y of the plate in the vertical sense.

$$\ell_1^4(d^4y/dx^4) + 2(D/D_o)\ell_1^2(d^2y/dx^2) + y = 0 \qquad (54)$$

Here D is the force of compression per unit of length perpendicular to the XY plane. The quantity ℓ_1 has the dimensions of a length, and, introducing the quantities hitherto adopted, namely, $\theta_1 = 3.27$, $E = 1{,}000{,}000\ kg/cm^2$, and $m = 4.1$, we obtain for $T = 30$ km the value of $\ell_1 = 52$ km.

Examining Equation (54) we find that for $D = D_o$ the solution is simple; y is then represented by a sine curve, and if we no longer neglect in this case the second and higher powers of (dy/dx), we see that for a slight increase of D the amplitudes quickly become greater. Obviously D_o is the buckling limit for the Earth's crust if it has no break or hinge; if D exceeds this limit the amplitudes become so large that in one of the waves the crust will yield. For our investigation we shall assume $D \leq D_o$, and to simplify our deductions we shall introduce the angle β as in (55).

$$(D/D_o) = \cos 2\beta \qquad (55)$$

We see that β can vary from 45° for D = 0 to 0° for $D = D_o$.

By substituting (55) in (54) we can derive the general solution as in (56A) for positive values of x; for negative x we find the same curve mirrored with regard to the Y axis. The origin in this solution in general is a discontinuity point. We assumed that the deformations disappear for x becoming infinite.

$$y = Ae^{-ax}\cos(bx + \varphi) \qquad (56A)$$

where A and φ are integration constants and a and b are given by

$$a = (\sin\beta)/\ell_1 \qquad b = (\cos\beta)/\ell_1 \qquad (56B)$$

By differentiating y with regard to x we find (56C) and (56D).

$$(dy/dx) = -(A/\ell_1)e^{-ax}\sin(bx + \varphi + \beta) \qquad (56C)$$

$$(d^2y/dx^2) = -(A/\ell_1^2)e^{-ax}\cos(bx + \varphi + 2\beta) \qquad (56D)$$

By integrating with regard to x, we obtain (56E) for the vertical force P_o, which has to work on the crust at the origin of coordinates to maintain the deformation as given by (56A).

$$P_o = -2\theta g\int_o^\infty y\,dx = -2\theta g\ell_1 A\sin(\varphi - \beta) \qquad (56E)$$

The length L of the waves represented by (56A) is given by (57).

$$L = (2\pi/b) = 2\pi\ell_1\sec\beta \qquad (57)$$

So we have for D = 0 a wave length $L = 8.90\ell_1$ and for $D = D_o$ a wave length $L = 6.28\ell_1$.

Applying these formulas to our problem, we can derive the integration constant φ from the condition that at the hinge point, that is, at the origin of the coordinates no force is working on the crust and so we have $P_o = 0$ or

$$\varphi = \beta \qquad (58)$$

A second condition is provided by the presence at this point of a hinge, which implies that the momentum of stresses M in the cross-section through the origin is zero. As the momentum M is proportional to (d^2y/dx^2) this condition gives $(d^2y/dx^2) = 0$ for x = 0. By using (58) we obtain $(A/\ell_1^2)\cos 3\beta = 0$. This condition leaves two possibilities:

$$A = 0 \qquad (59A)$$

or

$$\beta = 30^\circ \quad \ldots\ldots \quad (59B)$$

This means that the constant A must be zero as long as the compressive force D is smaller than the value corresponding to (59B), or, in other words, that in this case no deformation occurs. If D reaches this limit, however, all values of A are possible, that is, large deformations can originate. Obviously this value of D represents the buckling limit of the crust in this case. Indicating it by the index 1 and deriving its value from (55) in connection with (59B), we obtain (60).

$$D_1 = (1/2)D_0 \quad \ldots\ldots \quad (60)$$

By means of (52) and (53) we can express this value in the original data of our problem. Formula (60) gives us the important conclusion that the presence of a hinge line reduces the buckling limit of the crust to one-half of the value for the unbroken crust.

It is interesting to derive the deformation for this case. Introducing $\varphi = \beta = 30^\circ$ in (56A) we obtain

$$\begin{aligned} y &= Ae^{-x/2\ell_1} \cos\,[0.866(x/\ell_1) + 30]^\circ \\ &= Ae^{-x/2\ell_1} \cos\,[49.62(x/\ell_1) + 30]^\circ \quad \ldots \quad (61A) \end{aligned}$$

According, then, to (57), the wave length is

$$L_1 = 380 \text{ km} \quad \ldots\ldots \quad (61B)$$

Studying this deformation we see that the waves of buckling in this case die out quickly on both sides of the hinge point (see Fig. 26). So, if our assumption that a shear plane in the crust acts as a perfect hinge, the buckling force would be reduced to one-half of the normal value.

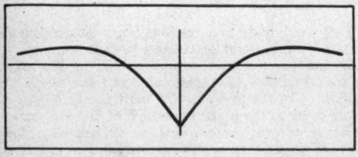


Fig. 26--Deformation due to buckling

This assumption will no doubt not represent the real circumstances in the Earth's crust. The thickness of the crust must bring about resistance to bending, even if the crust is intersected by a fault plane, but it must remain true that in this case the resistance is less than normal. It is difficult, however, to estimate the amount of lessening of the resistance, and so an exact treatment of the problem is hardly possible. We can say that in this case (d^2y/dx^2) does not disappear in the fault plane of the crust, that is, at the origin of the coordinates, but that we can probably obtain an approximation to the real conditions by assuming it to be proportional to the change of (dy/dx) in this area or, what amounts to the same thing, to the value of (dy/dx) for $x = 0$. Pursuing this way of solution, we find that thus the value of β for buckling must be smaller than 30° and that D is a larger fraction of D_0 than what we have found above; if the resistance to bending assumed at the origin tends to the normal value, β tends to 0° and D to D_0. We may conclude that as a shear plane in the crust is certain to diminish the resistance, the buckling force must be correspondingly smaller, but the amount of this decrease is difficult to derive.

This decrease of the buckling force, due to the presence of a crustal fault plane, must obviously cause the orogeny to follow this plane by preference, even if the compressive force is not perpendicular to it. Only if the deviation from the perpendicular direction is large can we expect folding to originate in an independent direction.

The above reasoning is further strengthened by the consideration that a large part of the crustal deformation in the orogenic belt must have a plastic character, and that the plastic flow which we have assumed to take place in the zones of crustal shear is likely thus to facilitate the coming into being of the tectonic deformation. This, therefore, is a second reason--and perhaps even a stronger one than the first--to expect that the orogeny will follow by preference the fault zones of the crust.

We have hitherto considered only the course we may expect the zone of strong crustal shortening to take. There can be no doubt, however, that, besides, a certain number of shear planes will become active again through the differential movements the crustal blocks must undergo. In many cases these shearing movements must also give rise to topographic features: (a) It may bring about renewed volcanism in these lines; (b) The roughness and the irregularities of the planes may cause material to be squeezed out during the relative movement of the two blocks on both sides of the plane; (c) A deviation from parallelism of neighboring planes, by the movement of the crustal block between in the sense of their converging, may give rise to compression of this block. Such a deviation as (c) may be present if the fault planes in the crust do not quite follow the directions of our Net, but even if they do, the planes are in general not exactly parallel; from Figure 7 we can derive that, to undergo compression, the block movement has then to occur in a direction away from the horizontal or vertical axis of this Figure. In our Net in Mercator projection these axes are found in the curves through the points of maximum stress on the equator; these points are marked by the indication 1.00. In the final case--probably more important than the two preceding ways in which topography may be imagined to originate--we may expect the coming into being of topography over shear planes, in which renewed movement occurs, if the orogenic force working on the crust has a component at right angles to the shear line. If the plane has a tilt with regard to the vertical this component must cause relative movements of the crustal blocks in a vertical sense, and, if the component is somewhat larger, we may perhaps even expect folding, although this must be slighter than in the main tectonic belt. We may probably find a good example of such a phenomenon in the crustal belt along the west coast of Sumatra, where evidence of folding has been obtained on some of the islands, while the gravity profiles over this belt seem to indicate a riding of the Sumatra block over the oceanic block. The crustal movements accompanying earthquakes in Sumatra nearly always occur along fault planes parallel to the belt; this confirms the conclusion that the principal part of the movement took place in this direction, that is, in the direction of the shear plane.

The fact that the topography in an orogenic belt may originate in numerous other shear lines besides the main zone of compression may give a simple explanation of at least part of the complicated pattern of the mountain formations known for most of the geosynclines on Earth. We may apply this to the alpine orogeny where the strike of the Dinarides, the Apennines, and the southeast-northwest part of the Carpathians might be explained by the pre-existing fault planes in the southeast-northwest direction of our Net, while fault planes in the other direction of the Net may well have played a part in the origin of parts of the other ranges, for example, in the course of the western parts of the Alps and of the Carpathians. From the amount of the compression in the different ranges we may derive that the general direction of the compression must probably have been south-southeast to north-northwest, although local deviations may possibly have occurred, and that it is likely that the crustal blocks of the Adriatic Sea and of Italy have had the greatest relative displacement with regard to the blocks north of the Alps. A more intensive study is required to make sure about these suppositions and to obtain further insight into these problems, but without doubt we may already state that the conception of a subcrustal current exerting its force on a system of separate crustal blocks with fault planes between, promises a better understanding of the intricate alpine orogeny than the hypothesis that forces have worked on an unbroken crust. In this last case it is difficult to explain the presence of the irregular field of forces needed to produce this pattern.

Southern Asia is another area where our hypothesis can give a better understanding of the trends of the Cenozoic orogeny; we may suppose that the mountain ranges of Baluchistan and Burma are connected with the corresponding directions of our Net which are also represented in the map of the main shear zones of the Earth in Figure 10, whereas the Himalayan Ranges must entirely have been brought about by the compressive forces. Here again the assumption of pre-existing fault zones in the crust helps to understand the pattern of the orogeny.

A further instance is provided by the East Indies and the Philippine Islands. As already mentioned, the gravity field as well as the topography show correlation with our Net and the part played by a few of the great shear zones, such as those along the west coast of Sumatra and the east coast of the Philippine Islands can explain the great arc formed by the orogeny. This is welcome, because the gravity anomalies point strongly to a single direction of the movement of the crustal blocks inside the great arc, namely, to the south-southeast, and not to a movement from the center towards the periphery, and so the origin of much of the orogeny, for example, that along the west coast of Sumatra where its direction makes only a small angle with the direction of the compression, is difficult to understand without the assumption of pre-existing fault planes in the crust.

We shall not here pursue this subject further. A more thorough investigation is needed as well as a detailed geological study in order to do justice to the difficult and many-sided problems involved in all these areas--something that can not be undertaken in the present paper.

A last cause leading to correlation of topography with the Net of shear planes in the crust is the way in which erosion is affected by the presence of shear planes. As these effects are clear, we shall not go deeply into this question here; SONDER'S paper [1938, p. 214 ff] gives a valuable discussion of it. He points out how the presence and "working" of the crustal fault planes must strongly affect the action of the erosion; this must bring about an orientation of the rivers and water courses in these directions. Figure 19 shows an example published by Hobbs; many others may be found in the papers of the lineament tectonicians mentioned in Chapter III. Sonder further deals with the effect of the fault planes on glacial erosion, which must likewise be strongly affected by it. Many examples are given by these same publications, of which three are represented in Figures 16, 17, and 20.

Our survey of the ways in which the origin and the presence of a system of shear planes can lead to a correlated topography is thus completed. The most difficult problem of all remains to be discussed, that is, the question of how we can explain the correlation of the continental coasts with our Net. We have seen in Chapter III that this correlation seems to be present although it is smaller than that of the topography as a whole. In attacking this question we are handicapped by the fact that the origin of continents and oceans is still an unsolved problem. On the other hand, we may thus hope that the solution of our present problem may shed light on this greater one.

Examining our problem more closely, we see that the correlation of the continental coast lines with our Net, or rather of the edges of the continental shelves, raises the difficulty involved in that the course of these shelf edges must be later than the shearing catastrophe of the crust and, therefore, later than the origin of a rigid crust of some thickness, whereas the geological, seismological, and gravimetrical data indicate strongly that the sialic layer is thinner for the oceans than for the continents and even is absent in a great part of the Pacific and, possibly, of the Arctic Ocean. We thus are confronted by the question of how it is possible that the course of the borders of these structural differences can have originated after the formation of the rigid crust. The gravimetric profiles observed at sea at about right angles to the continental coasts point in general indeed to the coincidence of these borders with the edges of the continental shelves.

Before trying to find an answer to this question, we may remark that the above-stated fact excludes the hypothesis that the continental sialic blocks originally formed a whole, and that a disruption of this mass, occurring in a period in which the basaltic layer was still plastic, gave rise to the formation of separate parts drifting away from each other and forming the continental blocks of today. A few authors, Osmond Fisher and others and recently B. G. Escher, have made this hypothesis in connection with the idea that at the moment the Moon broke away from the Earth a great part of the sialic mantle was carried off, while the remaining part broke into the separate blocks mentioned. The hypothesis, however, that at least the greatest part of the blocks thus formed had the contours of the present continents, is not compatible with our statement that these contours must have been formed after the formation of an entire rigid crust over the Earth.

Taking up our problem as to how this can have happened, the writer sees two possibilities; (a) that the formation of the continental sial blocks was as a whole later than that of the rigid crust and of the shearing catastrophe, and (b) that only their outline was formed later. For the first solution it seems that only one hypothesis is at present available, namely, that of RITTMANN [1939], but as this offers serious difficulties--as Umbgrove stated to the writer in a private letter, it is hard to understand the enormous sedimentation in the primitive oceans which, according to Rittman, must have led to the formation of the granite of the continents--we shall not discuss it further. The second possible assumption supposes that the greatest part, if not all, of the present continental contours has been formed by a tectonic folding orogeny, thus enlarging the sial continents by new zones of sialic material. As we have seen in the preceding pages that orogenic zones have a preference for following the trends of the fault planes in the crust, the correlation of the continental shelf edges with the Net of shear planes could thus be understood. The important question to answer is whether our assumption can be admitted with regard to our knowledge of the geology of the continental edges.

It is clear that this does not present any difficulty for all the coasts and shelf edges bordered by recent orogeny, such as the west coast of North and South America and the east coast of Asia. Where this orogeny is parallel to the coast we may admit at once that the direction of the shelf edge is determined by the trend of the orogeny. But even where the geology provides indications that the orogeny is cut off by the coast and sunk away, as, for example, to the northwest of Payta in northern Peru [STEINMAN, 1929; see also p. 52 of the present paper], a correlation of the coast line with the directions of our Net may obviously be expected also; it is clear that the presence of fault planes in the crust must favor the shear taking place along one of these planes. These mountain coasts can not in themselves, however, explain the percentage of the correlation found for all the coasts together. In Chapter III we have found that the percentage of the correlation for the mountain coasts apart is of the same order as that found for all the coasts, and so at least a great part of the other coasts must also somehow be connected with the Net of shear planes.

The question thus presents itself whether also for these coasts we may suppose that they have been formed by orogeny. In this case the tectonic activity of course must have occurred in one of the early orogenic periods before the Cambrian. From the radioactive determinations of age given by HOLMES [1937] and NIER [1938-39], KUENEN [1941] concludes that against three orogenic periods since the beginning of the Cambrian eight periods occurred in the preceding ages up to 1800 million years ago, and possibly still more have taken place before that date. So there have been many periods before the Cambrian in which unknown orogeny has occurred, and there is no reason to reject the idea that the other shelf edges may thus have been brought about in one of these periods. As we know that orogeny in successive periods has often shifted towards neighboring areas, we may perhaps see in the old Palaeozoic folding of the Brazilides running parallel to the shelf edge of the east coast of South America over a great part of Brazil to Uruguay, a slight indication in favor of an old folding determining the trend of this shelf edge. For the east coast of Africa such an indication might perhaps be found in the presence of the neighboring Carlsberg Ridge and Seychelles Bank, which by their curved form and the sial on their islands seem likely to be of orogenic origin. For the most northern part of the northwest coast of Africa an orogenic origin is known and so here the possibility of a correlation with our shear Net is evident. Concluding we may say that an orogenic origin of many, if not all, of the continental shelf edges seems possible.

We shall now consider our supposition in connection with two recently advanced theories about the origin of continents. In the first place we may mention UMBGROVE'S hypothesis [1942, pp. 104 ff], according to which the sial layer originally covered the whole Earth in about equal thickness and afterwards was thrust together in continental blocks by subcrustal currents. On this supposition he explains the three predominant levels of the topography at the Earth's surface pointed out by him, that is, (a) the depth of a great part of the Pacific and probably the Arctic Ocean where the sial is entirely absent, (b) the somewhat lesser depth of the Atlantic and Indian Oceans where probably a thin sial layer is present, and (c) the continental parts where the sial has been so much compressed that the blocks after subsidence in isostatic equilibrium rose above sea level. We can not assume that the sial in the Atlantic and Indian Oceans is the undisturbed original layer, for the compression of this layer in a measure corresponding to the area of the parts where the sial is lacking is insufficient to account for the sial blocks of the continents; we must, therefore, suppose that the layer in these oceans has been stretched by subcrustal currents or other causes or that the original layer had already thicker parts in those areas where the continents were formed afterwards.

Umbgrove assumes that the main compression leading to the growth of the continents has taken place at a time when the crust had not yet been entirely solidified. There is every reason to suppose, however, that the subcrustal currents have continued in later times and caused the periods of tectonic orogeny, and so our supposition that at least part of the continental edges have been formed in these later periods fits well with Umbgrove's hypothesis. One remark, however, must be made. If we accept the general view that the subcrustal currents producing the tectonic phenomena were caused by convection--a supposition forming also the basis of the explanation by GRIGGS [1939] of the periodicity of these phenomena--we must expect a higher temperature in the continental sial blocks with regard to the neighboring ocean crust because of the higher percentage of radioactive material of the sial and of the difference in the surface conditions, and this must have brought about rising convection currents below the continents and flown outwards below the continental edges. So these later currents must have had an opposite direction to those which, according to Umbgrove, in the first phase of the Earth's history caused the thrusting together of the sial blocks.

The second hypothesis about the formation of the continents has been advanced by the writer for the purpose of accounting for the curious systematic distribution of the continents on the Earth's surface. It has been noticed long ago that in general the continents have oceanic areas at their antipodes, for example, North America, the Indian Ocean, Australia, the North Atlantic, Antarctica, the Arctic Ocean, etc.; only five per cent of the continental areas form an exception to this law. It further strikes us that the distribution has somewhat the character of a tetrahedon, the four corners being represented by the Siberian Shield, the Canadian Shield, the Scandinavian Shield, and the Antarctic Continent, the continents having more or less a triangular shape pointing southward and their bases forming a ring in the north which finds its counterpart in the ring of water around the Antarctic Continent [STEERS, 1932; UMBGROVE, 1942, pp. 81 ff]. As is well known, Lowthian Green has tried to explain these peculiarities by the hypothesis that because of contraction the Earth tries to assume the shape of a tetrahedon, and De Lapparent, Gregory, Arldt, Dacqué, and Kober later supported this or similar theories. The theoretical basis is hardly acceptable, however, and a still stronger objection may be found in the fact that the geoid does not show any perceptible bulges in the corners of a tetrahedon; the sial crust is in isostatic equilibrium, and so the elevations are not caused by an outward bending of the crust but by its being thicker in those parts. The hypothesis, therefore, no longer finds support.

The writer has proposed [VENING MEINESZ, 1944] another explanation which seems to him to be more tenable. It starts from the assumption that the formation of the continents has been connected with the system of convection currents which we may suppose to have been present in the Earth during its first cooling phase. JEFFREYS [1929] supposes that at that time the nickel-iron core had already been formed and on that basis we may suppose that the currents took place in the mantle of 2900 km outside this core. By means of a solution for convection currents in the sphere on the same lines as LORD RAYLEIGH'S [1916] solution for a plane layer, we can show that a system of four rising currents and four descending currents, each of them covering an octant, is the most probable under these conditions. Antipodal to each rising octant is a descending one, and the centers of the four rising octants form the corners of a tetrahedon as well as those of the descending octants. So we see that, admitting the connection with the formation of the continents, the above-mentioned peculiarities in the distribution may be explained.

Kuhn and Rittmann have expressed serious doubts that the nickel-iron core of the Earth could have differentiated during the time elapsed since the beginning of the Earth's history, and they certainly can not accept the possibility of its having done so in the relatively short time estimated for this event by Jeffreys. If we admit the validity of their arguments, we come to another picture of what has happened. We then must suppose that the octant system of convection currents has originated for some reason or other, perhaps because of its being the only perfectly regular distribution of areas of more-or-less equal dimensions in all senses, over the Earth's surface where in every corner point an even number of areas come together, while for our system of currents such a number is obviously necessary because otherwise two areas of the same kind--rising or descending--would be adjoining each other. Once having admitted the formation of this system of currents, it follows from the above-mentioned equations for convection currents that they must have extended to a depth of about 2900 km and below this depth the solar material, rich in hydrogen, according to the views of Kuhn and Rittmann, would have remained unchanged; it forms the heavy core of the Earth, and the abnormal properties of the core revealed by seismology seem to be in accordance with this idea. The currents in the mantle could explain that differentiation has extended down over its whole depth to the core.

Examining the connection of the system of convection currents with the formation of the continents, it is clear that it is easy to bring it into harmony with Umbgrove's hypothesis; the currents provide the cause for the thrusting together of the sial layer supposed by Umbgrove to have led to the forming of the continental blocks. These blocks must then be assumed to have originated above the descending currents. We thus arrive at a satisfactory incorporation of the explanation of the tetrahedral distribution in this hypothesis. Two points, however, deserve our attention. In the first place we may presume that the concentration of sial, which is rich in radioactive matter, above the descending column must in the long run have brought about a rise of temperature with regard to the areas above the rising column, and so it seems doubtful whether the currents could have continued to flow in the same sense. As a change of the direction of flow would have destroyed the sial concentrations at the surface we must suppose that, before such a change could have occurred, the solidification of the crust prevented this from taking place. This is in harmony with Umbgrove's view that the continental sial blocks must have been formed before the crust as a whole had solidified. A second more difficult point is the problem of understanding how the rising current below the Atlantic and the Indian Oceans could have brought about a stretching of the original sial layer without taking it away entirely.

We can also suppose another connection between the formation of the continents and the system of convection currents which has the advantage that change in direction of flow need be assumed; it is based on the following hypothesis regarding the origin of the continental sial blocks. Assuming that the currents have formed before the sial layer, we shall suppose that the sial was brought to the surface by these currents and that the temperature there was such that the solidification of the crustal layer prevented the flowing out of the sial in a continuous layer over the Earth, or that at least the viscosity was high enough to prevent this. We may in this case expect the forming of the continental sial blocks above the rising currents. The thinner layer below the Atlantic and Indian Oceans could have originated in the beginning when the cooling was less and the flowing out still possible over part of the Earth's surface. The gradual rise of temperature to be expected in the continental blocks with regard to neighboring areas, because of the greater amount of radioactive material in the sial, would tend to stabilize the system of currents.

We shall not enter here into a more detailed discussion of this hypothesis, but we may remark that like Umbgrove's it may be brought in harmony with our supposition about the origin of the continental edges. Here again we must consider it likely that the currents have continued to occur in the later periods of tectonic orogeny, and that many of these edges have been formed by the thrusting together of the sial crust by these currents. For this hypothesis these later currents can be supposed to have flowed in the same direction as the original ones, for in both cases the direction must have been away from the continent.

We may conclude that for Umbgrove's hypothesis, as well as for that of the writer, the formation of continental edges correlated with the shear pattern could be explained.

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THE READJUSTMENT OF EUROPEAN TRIANGULATION

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Abstract--A proposed plan for the readjustment of the European network of triangulation is presented. A discussion of the Central European triangulation readjustment which is in progress is followed by a general outline for an expansion of this project to include all of Europe west of 32° east longitude. The outline includes suggestions for the adoption of a preliminary datum followed by the determination of the final datum using the Bowie method of adjustment with whatever modifications are necessary.

European countries are far advanced in geodetic engineering. In general, each has completed in years past its basic framework of first-order triangulation. Leading European geodesists for many years have contemplated the benefits which would surely accrue to all nations concerned if some international agreement could be worked out whereby the entire area would have its basic control computed on a single geodetic datum. This common datum implies a common figure of the Earth and a common unit of length.

Until the present time, each country has followed its national inclination and has selected for its datum some observed astronomic position, usually in its capital city. From this point, its basic triangulation has been computed geodetically to its borders. The astronomic datum thus used as a geodetic initial leaves uncorrected the error in position arising from the deflection of the plumb line. This, coupled with the known tendency for an arc of triangulation, as it moves forward, to accumulate a twist in azimuth, causes a disparity at the frontier with each contiguous nation. This difference in geographic position, which is made inevitable by the computation of European control on three different ellipsoids; namely, the Bessel, the Clarke Spheroid of 1880, and the International Ellipsoid, is known to amount to as much as 500 meters at one European frontier. Such discrepancies, with their attendant inconveniences and potential sources of international misunderstanding, are caused directly by the lack of a common geodetic datum. It is now proposed to eliminate all of these misfits through a general least-square adjustment of the basic arcs in the European first-order triangulation (see Fig. 1). No lower-order control is involved in the present plan. Once the stations of the basic overall framework in Europe are brought mathematically into consistent relationship with each other, the fruits of the international cooperative effort will have been achieved. Each country will then be in a position to proceed independently, when and if it sees fit, to adjust its own supplemental control and to retain to itself the resulting information.

There should be no reluctance to proceed with the cooperative work from the standpoint of possible military significance. First-order geodetic and astronomic data from the beginning have been considered primarily by all nations to have scientific rather than military interest. This is evidenced by the fact that such information has been freely published even where lower order control has been held under security classification. It should be emphasized, therefore, that none other than customarily published data will be involved in the proposed European readjustment.

In April 1945, the Houghteam, an intelligence unit of the Office of the Chief of Engineers, United States Army, in cooperation with SHAEF and the British War Office, undertook a readjustment of the Central European first-order triangulation, using the personnel and facilities of the trigonometric section of the German Central Survey Office. Friedrichsroda, a small town in Thuringia, had just been captured by the United States Third Army. Here was found the geodetic unit of the Reichsamt für Landesaufnahme. The director of this unit, Diploma Engineer Erwin Gigas, together with the nucleus of his personnel and their immediate families, were evacuated by the Houghteam to Bamberg in the United States Occupation Area. All pertinent triangulation records were transported to Bamberg. Suitable office space and quarters were requisitioned from the Bürgermeister. Salaries were established at former German Civil Service levels, and the personnel were placed on the Bürgermeister's pay roll following clearance of each individual by the Counter Intelligence Corps.

Gigas, an internationally known geodesist, was directed to resume immediate charge of the reconstituted unit. He was relieved at once from any allegiance he might owe to his former German chief, the president of the Reichsamt für Landesaufnahme. Gigas was ordered to begin preparations

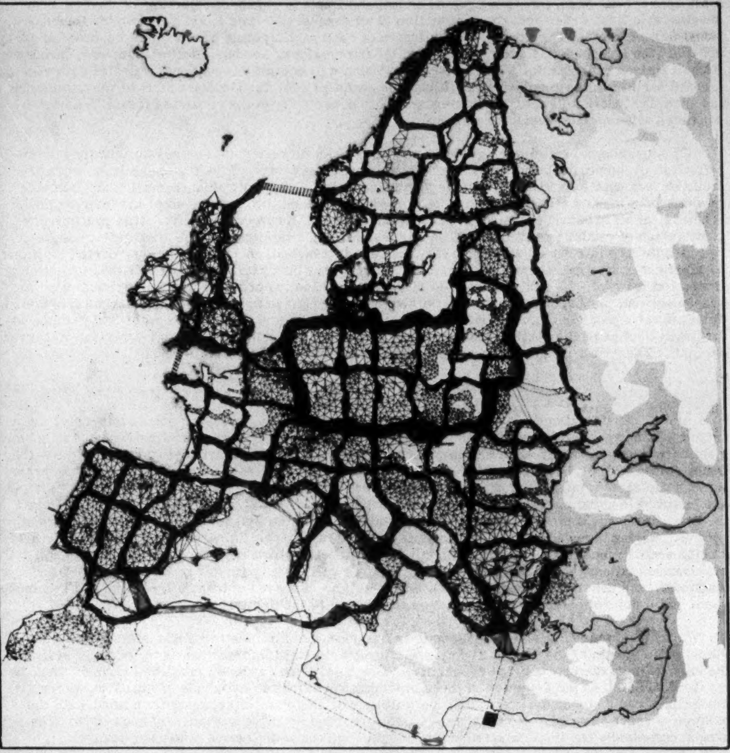

Fig. 1--European net of triangulation, showing sectional arcs and junction figures

for a readjustment of the Central European triangulation and to employ the Bowie junction method [see "Reference" at end of paper, ADAMS, 1930] which had been used successfully in the United States. Fortunately, a large quantity of first-order astronomic stations at which azimuths had been observed and an adequate number of first-order bases existed in the German triangulation. These surveys dated back over a century. Gigas and his assistants began an exhaustive study of these observed values to determine their relative reliability. A certain few were rejected where there were indications that they fell below first-order specifications. Since the German triangulation had been carried out as area control rather than by individual arcs, it was necessary to select from the area control certain arcs which would form the framework of the proposed adjustment by the junction method.

Subsequent to the return of the Houghteam to the United States in September 1945, the Bamberg project has been administrated and inspected regularly by the Intelligence Division, O. C. E., USFET. Technical supervision has been continued by the Geodetic Division of the Army Map Service. Gigas has submitted regular monthly reports of progress.

Following is an outline of the sequence of operations involved in the current Central European readjustment, which is applicable in every detail to the proposed European readjustment. There are ten major steps.

(1) Detailed study of records; selection of integral parts of basic framework, including the most appropriate arcs, junction figures, bases, and Laplace stations; rejection of any work of questionable first-order accuracy; reduction of all measured bases to sea level on the International unit of length. The geodetic commission of each participating nation would be asked to carry out this step independently and to present to the International Geodetic Staff at Bamberg, through its own liaison expert, a folio in concise form which will contain all pertinent selected data recommended for use in the readjustment. It may be necessary for the Geodetic Staff to vary somewhat the arcs and junction figures recommended in order properly to correlate the ties with adjacent countries into one continuous framework.

(2) Assuming a preliminary geodetic position, which is believed to be reasonably free from deflection of the vertical and which is preferably near the center of the European framework, to facilitate computations in all directions simultaneously by numbers of mathematicians, compute geodetic positions on this preliminary datum, which includes the dimensions of the International Spheroid, of all accepted astronomic stations in the entire European network. This preliminary computation of geodetic positions will be carried through a minimum of the strongest triangles. New lengths are introduced as each measured base is reached. A mean value of geodetic positions by different routes is determined occasionally throughout the framework, and this mean position is carried forward. As each astronomic station is reached, where a first-order azimuth also has been observed, the Laplace equation is solved and a correction to the astronomic azimuth obtained. The Laplace equation is formed by equating the two expressions for the prime vertical component for the deflection of the vertical, one from the observed longitude and the other from the observed azimuth. The resulting equation for west longitudes may be stated as follows:

$$\alpha_G = \alpha_A + (\lambda_A - \lambda_G) \sin \phi_G \ldots\ldots\ldots\ldots (1)$$

α, ϕ, and λ denote azimuth, latitude, and longitude, respectively, while the subscripts refer to astronomic and geodetic values. Studies have shown conclusively that while first-order astronomic longitudes and astronomic azimuths may be observed and geodetic longitudes carried through the triangulation with probable errors of about 0.5 of a sexagesimal second, geodetic azimuths carried through the same triangulation are subject to errors ten times as great. It is on this basis that we are justified in using the Laplace equation to correct observed astronomic azimuths to minimize the twist in triangulation which occurs almost invariably in the extension of an arc of horizontal control. Having thus determined the Laplace correction, the preliminary geodetic position is held and the new corrected, or Laplace, azimuth is used to carry forward the position to the next astronomic station. When this step is completed, we will have computed geodetic latitudes and longitudes on a consistent preliminary datum as well as observed astronomic positions of common points for a determination of the correction in position to the preliminary datum.

(3) Solve for the Σ(A - G) (astronomic minus geodetic) minimum to eliminate so far as possible the deflection of the vertical. Any available gravimetric information as to local deflection of the vertical may be incorporated at this step. Great care and judgment must be exercised here by the Geodetic Staff in the selection of these astronomic stations to avoid use of locations where the topography would obviously exert an undue influence on the plumb line, keeping in mind that the position correction arising from the (A - G) and gravimetric solutions must be such as to free almost completely the final selected datum from the effect of deflection of the vertical.

(4) Apply the Σ(A - G) corrections to each of the geodetic latitudes and longitudes of the astronomic stations computed under Step (2), above, including the preliminary initial station.

(5) Where a Laplace azimuth and a measured base are not found within a junction figure, carry weighted values into the junction from adjacent locations; make a least square adjustment of each junction figure using side and angle equations. Starting with the geodetic position made available from Step (2), and using the length and the new Laplace azimuth, compute the new preliminary positions in the junction figures. We now have the lengths and azimuths to control the common lines with the intermediate sectional arcs.

(6) Adjust the sectional arcs by employing angle, side (where required), length, and azimuth equations, holding fixed the previously computed azimuths and lengths of those outer lines common with the junction figures as well as any previously selected Laplace azimuths or measured bases which may exist within the sectional arcs. In setting up condition equations at this step, the coefficients for latitude and longitude conditions should be included to facilitate later solution.

(7) Since the sectional arcs forming a loop were adjusted separately, the loops will not close exactly in position. We are now ready to determine through the solution of observation equations,

the most probable geodetic position of one point in each junction figure. Starting with a geodetic position in each junction figure resulting from Step (4), carry a computed geodetic position through each sectional arc to the next junction figure. Two observation equations are now set up, one for the latitude and the other for longitude closures. There will be as many pairs of observation equations as there are sectional arcs. Weights should be assigned in accordance with the weights of the latitude and longitude conditions in each sectional arc. The solution of these two sets of observation equations will give changes in latitude and longitude to the preliminary positions, which resulted from Step (4), for one station in each junction figure. A constant correction is then determined which will reduce the algebraic summation of these changes to a minimum. The correction is applied to all these changes plus the temporary initial change which had been considered as zero. This procedure eliminates the effect of considering any one point as a permanent initial. These revised changes will now give the final geodetic position of the one selected station in each junction figure.

(8) Compute the final geodetic positions of the stations in the junction figures, after first having perfected the azimuth through the use of the final geodetic longitude in the Laplace equation.

(9) Readjust the sectional arcs to include position equations, with a small constant in each azimuth equation due to the new Laplace correction, thus fitting the arcs into consistent relationship with the junction figures. Compute final geodetic positions of all stations in the sectional arcs.

(10) Prepare final lists of geographic positions for the entire European framework of first-order triangulation, including lengths, azimuths, and back azimuths.

The ten steps just presented are intended as an outline of the proposed plan of operations. (Some variation in the Bowie method is essential due to the fact that no previous adjustment to a common datum exists in Europe.) It is likely that the Geodetic Staff will evolve certain other variations and improvements, but the general plan will be maintained. The proposal to adjust all of the published European first-order triangulation west of Meridian 32° east longitude on a common geodetic datum is not new. That illustrious citizen of France, the late General Georges Perrier, who was held in high international esteem for his many contributions to science and whom many of us were fortunate to know and revere as a personal friend, had long envisioned and worked for a general geodetic adjustment of European control.

The time is now believed propitious to carry on this international program to complete success. The project is not visionary as a possibility for the distant future; a highly efficient organization exists already at Bamberg and has been in operation on the Central European nucleus of the framework for more than a year under technical supervision of the Chief of Engineers, United States Army. The present proposal is merely an expansion. There are some 35 German geodetic engineers and mathematicians employed on the work. The junction method of adjustment lends itself readily to rapid progress through the employment of maximum personnel. It is estimated that the entire program can be completed by the end of 1948. The cost is borne entirely by the Germans. In view of the proposed extension of the current Central European readjustment, it was recommended at a preliminary conference in Bamberg on May 27, 1946, that an International Geodetic Staff, to consist of one geodetic expert from each cooperating country, be set up at Bamberg to assume technical control of all operations, with Gigas and his assistants as consultants only. German mathematicians and computers would continue to handle the routine work of the readjustment with all technical policies and supervision in the hands of the International Staff. Since Bamberg is in the United States Military Occupation Area, administrative supervision would continue as a function of the Chief Engineer, O. C. E., USFET. The general program would conform to broad policies of the Allied Control Council through its Multipartite Survey Committee.

In the past, there has been some discussion on the selection of a single, centrally located international datum for Europe. Reflection on this subject will show that with the completion of a general adjustment of the type proposed, there exists no one location which may be construed as the initial datum point to the exclusion of others. Any station of the framework in any country has equal claim to the European datum point due to its consistent relationship mathematically with all others. A common geodetic datum is a condition of the whole; it is not pertinent to a single station.

The status of the current Central European readjustment is such that operations on the expanded program, if approved, should be commenced by October 1, 1946, to avoid backtracking.

In view of the advanced progress of operations on the Central European readjustment, the following recommendation for definite action is presented to the members of the Conference:

Formation of a Committee on the Readjustment of European Triangulation, composed of one geodetic expert from each interested country without regard to whether such country adheres to the International Union of Geodesy and Geophysics. The Committee should be set up as early as appointments can be effected. It should be a "working" committee, with specific instructions to examine fully into the triangulation readjustment problem of Europe both from technical and operational standpoints. It should be directed to make its report and recommendation to the General Secretary within six months of its inception and not later than May 1, 1947.

There is little need to outline further to geodesists the benefits to be derived from a consistent mathematical adjustment of continental control surveys on one common datum. The scientific value alone of long triangulation arcs, as it pertains to the study of the figure of the Earth, is great. The present opportune situation should not be permitted to pass without cooperative action to achieve what has been long visualized as a vital geodetic program for Europe.

In conclusion, the writer wishes to acknowledge much valuable assistance received in the review of this paper by H. W. Hemple, Chief of the Division of Geodesy, and by C. A. Whitten, Chief, Section of Triangulation in the Division of Geodesy, both of the United States Coast and Geodetic Survey, and by John A. O'Keefe, Chief of Research and Analysis Branch, Geodetic Division, Army Map Service.

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Army Map Service,
Office of the Chief of Engineers,
Washington, D. C.

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AUTOMATIC RANGE SWITCHING EQUIPMENT FOR THE GRINNELL WIND-SPEED RECORDER

Ronald L. Ives

(Published by permission of the Chief, Chemical Warfare Service, United States Army)

Abstract--Equipment and methods for automatically changing the wind-speed range of the Grinnell condenser-discharge wind-speed recorder to accord with the prevailing average wind speed are here outlined, with salient empirical theory. One automatic range switch is described in working detail, and two others are briefly outlined. Other applications of the general principles employed are mentioned.

Introduction--Development, in 1944, of a condenser-discharge wind-speed recorder, operating on principles similar to those of the United States Weather Bureau condenser-discharge average wind-speed indicator [see "References" at end of paper, MIDDLETON, 1942], by S. W. Grinnell, of Stanford University, produced an instrument, now known as the Grinnell Recorder [GRINNELL, 1945], having wide applicability to both routine and research anemometric problems.

Recorder principles--Circuit diagram of the Grinnell Recorder is shown in Figure 1. Here closure of the anemometer contacts operates the relay at the left through the local circuit (not shown) and pulls down the armature. This charges the impulse condenser, C_1, from the battery, E. Opening of the anemometer contacts releases the relay armature, applying the charge on C_1, through the current limiter, R_1, to the smoothing condenser--instrument circuit (C_2--Rm). Instrument indication at any given time is determined by the charge upon C_2, which is a function of its rate of replenishment from C_1, all other factors remaining the same. Frequency of charge replenishments is determined by, and is the same as, the frequency of anemometer contact closures. Time constant of the instrument circuit, which determines its averaging ability, is the product of the smoothing capacity, C_2, and the instrument resistance, Rm. Relation of instrument indication to average frequency of anemometer contact closures is shown by Grinnell's formula:

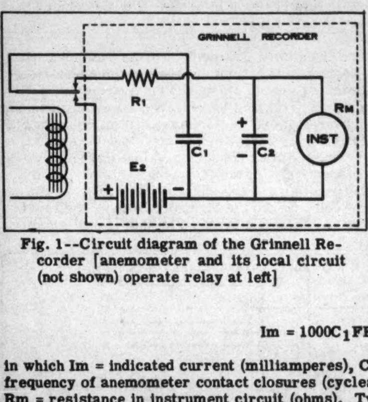

Fig. 1--Circuit diagram of the Grinnell Recorder [anemometer and its local circuit (not shown) operate relay at left]

$$Im = 1000C_1FE/(1 + C_1FR_m) \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which Im = indicated current (milliamperes), C_1 = capacity of impulse condenser (farads), F = frequency of anemometer contact closures (cycles per second), E = battery voltage (volts), and Rm = resistance in instrument circuit (ohms). Typical operating constants for various anemometers and speeds are given by GRINNELL [1945].

Range needs and properties--Field studies in a number of areas disclose the presence of several diurnal wind-speed (and direction) regimes having markedly different average speed values, so that speed records made on an instrument having a linear or quasi-linear scale (as does this one) will crowd the lowest speed regime toward the bottom of the scale, where interpretation and detection of variations is difficult and time-consuming. This is particularly undesirable where the relative, rather than the absolute, wind-speed change must be determined. This difficulty can be reduced or eliminated by use of two speed ranges, one that of the instrument alone, the other that of the shunted instrument (with various auxiliaries).

Selection of ranges is made from previous wind records (if such are available). A low speed range of 0 - 15 mph and a high range of 0 - 75 mph will be satisfactory in many areas, and will be used here as an example. To prevent repeated switching back and forth between ranges when the wind speed oscillates about low range top mark, producing a record that is extremely difficult to interpret, some overlapping of ranges is desirable. In the medium speed range, in many areas, short-term speed variations do not frequently pass the approximate limits $S\sqrt{2}$ and $S/\sqrt{2}$, S being the average speed for the wind regime. Using this approximation, the high-to-low transfer, or switch-back point, is set at $15/\sqrt{2}$, or, for convenience, ten mph. Other selections of transfer points and overlaps may be made, within the limitations of the equipment, to suit record needs and local wind conditions.

Use of two speed ranges, although simplifying chart interpretation, requires either the presence of an alert operator in continual attendance at the recorder, or an automatic speed-operated range switch.

Shunts and auxiliaries--Indication of any standard moving-coil instrument may be reduced to 1/N of its previous value by shunting the instrument with a resistor valued at $Rs = Rm/(N - 1)$, in which Rs is the shunt resistor and Rm is the movement resistance. This is the conventional shunt formula.

Whenever the range of the Grinnell Recorder is altered by changing the electrical constants, a new calibration is required. This is not a serious difficulty. Simple shunting of the movement, however, also alters the time constant, so that the records made in the two ranges are not strictly comparable.

Time constant can be restored by adding capacity across the instrument, which is a costly and bulky procedure, although at least theoretically workable; or by inserting a resistor in series with the shunted instrument movement, to restore the resistance across the smoothing condenser, C_2, to its original value, Rm. This is inexpensive and entirely practicable. The value of this series resistor, Rx, is found from $Rx = Rm[(N - 1)/N]$. With this resistor in series with the shunted instrument, time constant of the recorder is the same in both ranges.

Automatic range switching recorder--Complete circuit of a Grinnell Recorder equipped with an automatic range switch is shown in Figure 2. Anemometer circuit consists of the anemometer, the battery, E_1, and the relay, 1. When the anemometer contacts close, the relay armature pulls down, closing the lower contacts of each set. Contacts A (relay 1); battery, E_2; impulse condenser, C_1; current limiting resistor, R_1; smoothing condenser, C_2; and the instrument, Rm; constitute a recorder identical with that of Figure 1, except that a series resistor, R_2; and a shunt resistor, R_3; have been added to alter the range while preserving the time constant. Values of these two resistors, R_2 and R_3, are found from Rx and Rs, respectively, of the foregoing section. On the low speed range, the series resistor, R_2, is short-circuited, and the shunt resistor, R_3, is disconnected, by the "up" position of the A contacts of relay 3. On the high speed range, the short across R_2 is removed, and R_3 is shunted across the instrument movement by the "down" position of contacts A of relay 3.

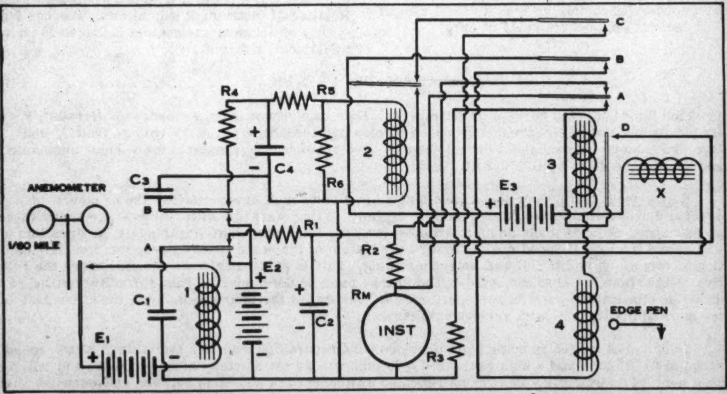

Fig. 2--Grinnell Recorder equipped with an automatic range switch [symbols of the recorder components in this figure agree with those in Figure 1]

The upper circuit, controlled by the B contacts of relay 1, is another condenser-discharge device, consisting of impulse condenser, C_3; current limiting resistor, R_4; smoothing condenser, C_4; and an instrument circuit consisting of R_5, R_6, and relay 2, which here is a contacting milliammeter. Both condenser-discharge circuits share battery E_2. This upper circuit controls the range switching relay, 3.

Although an almost infinite number of variations is possible, standard operation requires that the frequency and time characteristics of the recorder and range control components be equal. This is best attained by using components of equal value in comparable locations, and by evaluating R_5 and R_6 so that the resistance across C_4 equals that across C_2.

Sensitivity of relay 2 is modified by the shunt, R_6, and resistance across C_4 made equal to that across C_2 by adjustment of R_5. Drop point of 2 (upper contact closes) is set for operation when the recorder reaches the predetermined high-to-low transfer point (evaluated from 1). Pull in point of 2 (lower contact closes) is set for operation when top mark of the low range of the recorder is reached.

When all components are connected and adjusted, and the instrument manually set for low range, a slow acceleration of the anemometer will cause the recorder pen to approach top mark slowly. Simultaneously, current through 2 will increase, bringing it closer to the pull-in point. When the pen reaches the top of the low range, the contacts of relay 2 pull in, closing the lower circuit, which energizes relay 3 through contacts D, which are closed only when all main contacts (A, B, and C) are in "up" position. All main contacts of relay 3 move to the "down" position and lock there, the latch opening contacts D. This, through contacts A, removes the short circuit from R_2, and shunts R_3 across the recorder movement. Once the main contacts of 3 are latched down, no more current is drawn by the relay until the release circuit is actuated. Details of operation of this special latching relay circuit have been described elsewhere [IVES, 1945].

When, with the recorder on high range, the anemometer speed decreases, the recorder pen moves toward zero, and current in relay 2 declines toward the predetermined drop-out point. At this point the upper contacts of relay 2 close, energizing release coil X, of relay 3, through the main contacts, C, of the same relay. All main contacts of relay 3 go to upper position. A contacts disconnect the shunt, R_3, from the recorder and short circuit the series resistor, R_2, restoring it to low range. C contacts open, de-energizing the release circuit, and D contacts, controlled by the latch, close and remain closed. The recorder is now on low range and will remain so until the speed rises to top mark.

To prevent confusion of ranges while interpreting the chart, one of the recorder edge pens is connected for control by the B contacts of relay 3, so that it moves to inner position when the recorder is on high range. This indicates plainly on the chart which range is in use.

The battery E_3 which controls the range switching relay, and battery E_1 in the anemometer circuit, may be a single battery if component operating voltages are identical.

Other methods--Several alternative range switching circuits are practicable, although, in general, the one outlined above will give the best service with the least trouble.

The contacting milliammeter, 2 (see Fig. 2), can be connected in series with the recorder circuit, ahead of all range modifying resistors, and used, in that position, to control the range relay. This is electrically simpler than the method outlined above, but raises the resistance of the recorder circuit appreciably and is subject to vicious junting when the damping periods of the two movements are unequal.

A second alternative is to interpose a submultiple contactor [IVES, 1946] between the recorder circuit and the anemometer relay, so that the anemometer relay operates the submultiple contactor, and the output of the submultiple contactor functions as the A contacts of relay 1 in Figure 2. This arrangement permits the use of the same calibration curve for both ranges, and is capable of very wide variations as to range ratios. Series and shunt instrument resistors are omitted in this arrangement, and the submultiple contactor is inserted into or removed from the circuit by the range control relay, 3. Submultiple contactors, although extremely useful in some work, are noisy, demanding of power, and have a relatively short life (100,000 operations or so) between shutdowns.

Other applications--The upper condenser-discharge circuit, here used to control the range-switching equipment, can be used as an alarm to warn of high or low speed, either alone or in conjunction with the recorder. Coupled to almost any rotating, reciprocating, or progressing contacting device, the recorder, either with or without the range switch, can be used as a measuring instrument, and the range switching device can be used to perform a variety of operations, either alone or in addition to its function as a range switch.

Conclusions--The equipment outlined in the foregoing sections is capable of extending the useful range of a continuous operation unattended wind-speed recorder so that, without crowding the low speed records, it will record all speeds likely to be encountered in the field, and will indicate plainly on the chart which speed range is in use. By overlapping the ranges appreciably, chart reading is not unduly complicated even when the wind speed oscillates about either change point. Possible alternative circuits are presented for use in special problems; additional uses of the recorder, and of the range control device, are mentioned.

Acknowledgments--The writer is indebted to S. W. Grinnell of Stanford University for many valuable discussions of the problems involved in this and related instrument developments.

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RADAR STORM DETECTION

Harry Wexler

Abstract

Radar photographs of thunderstorms and the Florida hurricane of September 1945 were shown to illustrate structure of these storms (see Fig. 1). The relation between radar echoes and the reflecting material in the storms was discussed. Previous research has shown the intensity of the return radiation, among other things, to be proportional to the number and sixth power of the diameter of the intercepted water droplets. For radar frequencies now in usage, this means that only water drops large enough to fall out as precipitation reflect a detectable echo. The possibility of determining distribution and intensity of precipitation during a given storm by radar was discussed, but it was concluded that this cannot be done on an absolute basis at present, but that the relative intensities can be determined by suitably modified radar. However, if observed rainfall intensities are available at a small number of stations in the area swept by the radar, then it is possible to "calibrate" the radar intensities in terms of rainfall intensities.

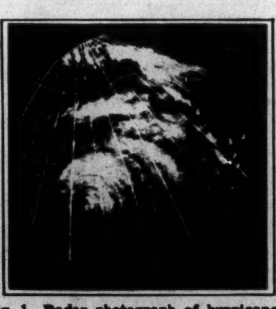

Fig. 1--Radar photograph of hurricane of September 16, 1945, as it appeared 130 miles south of radar station at Orlando, Florida [Army Air Forces]

U. S. Weather Bureau,
Washington, D. C.

(Abstract received January 9, 1947; paper presented in full at the meeting of the Washington Group, Section of Hydrology, Washington, D. C., December 3, 1946.)

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VARIATIONS IN SPORADIC-E IONIZATION OBSERVED AT WASHINGTON, D. C.

M. Lindeman Phillips

Abstract--Variations of sporadic-E ionization observed at Washington, D. C., were investigated with respect to diurnal, seasonal, and both long-period and short-period solar-activity variations, as well as variation of fEs above a given frequency with the frequency.

Maximum values of sporadic-E ionization were observed during periods of minimum solar activity, with marked rise in the percentage of time of occurrence of average night-time fEs in excess of three Mc (seven per cent per degree of heliographic latitude) with decreasing average heliographic sunspot latitude below 11°.6. Maxima in this quantity occur during both solstices, that during summer solstice being the greater; minima occur at both equinoxes. The solstice-equinox variation is in fair quantitative agreement with the variation of fEs with average heliographic latitude of sunspots for a latitude change equal to the solstice-equinox change in latitude of the center of the solar disc. Both seasonal and long-period solar-activity variations thus suggest that sporadic-E ionization may be principally caused by solar corpuscular radiation from regions near the solar equator.

Short-period variations in sporadic-E ionization with solar activity show direct proportionality near the solstices, and slight inverse proportionality near the equinoxes.

Slight increases in the ratio of monthly- to yearly-average values of percentage of time of occurrence of fEs in excess of three Mc for the months of August, October, and November, above those indicated in the regular seasonal variation for other months, may indicate some ionization caused by meteoric bombardment.

The logarithm of the percentage of occurrence of fEs in excess of a given frequency is inversely proportional to that frequency, this variation with frequency being more pronounced around the equinoxes than around the solstices.

As a measure of the intensity of sporadic-E ionization, it has been customary to use the upper-limit frequency of vertical-incidence reflection from sporadic-E layer heights, although it is known that this quantity, especially for low values, may sometimes be of doubtful significance because of variable ionospheric absorption, and because of ambiguity in cases where the f^oE and f^xE are not definitely observable. The upper-limit frequency for vertical-incidence reflection by means of sporadic-E ionization, or fEs, has been regularly scaled for each hour of the day at Washington, D. C., since May 1935, thus presenting the longest series of these data available for any location.

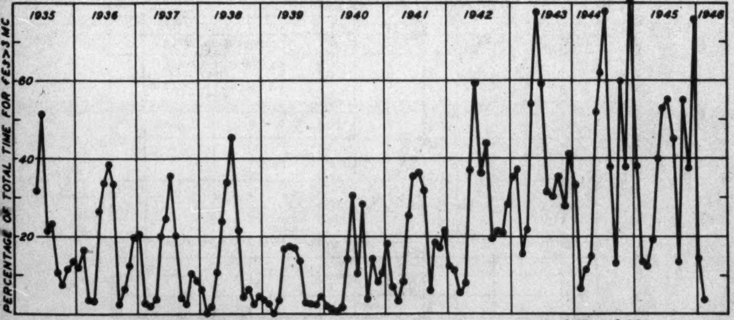


Fig. 1--Time variation of percentage of total time of occurrence of fEs > 3 Mc, 18^h00^m through 06^h00^m, 75°W Meridian Time, at Washington, D. C.

Study of the time variations of these data for any given location shows that they consist of (a) long-period variations with long-period variations of solar activity, (b) short-period variations with short-period variations of solar activity, (c) seasonal variations, and (d) diurnal variations.

During daytime hours, there may frequently occur masking of the upper-limit frequency of vertical-incidence reflection by Es, by reflection from the regular E layer. For this reason, long-period and short-period variations of fEs with solar activity, as well as seasonal variations, are generally best indicated by the prevalence of fEs above three Mc during the local time 18^h00^m - 06^h00^m, where such masking is negligible.

Time variation of the percentage of total time for fEs > 3 Mc during the hours 18^h00^m - 06^h00^m, inclusive, at Washington, D. C. is shown in Figure 1. It may be seen that there is greater prevalence of fEs > 3 Mc during times of minimum solar activity than during times of maximum solar activity, and greater prevalence near the solstices than near the equinoxes, the prevalence near the summer solstice being the greater. Moreover, although not shown here, these variations are true not only for the sum of the data between the hours 18^h00^m - 06^h00^m, but also for the individual sets of data for any one of the hours during this period.

In order to separate variations with solar activity from those associated with seasonal change, twelve-month running averages were computed of the percentage of total time of occurrence of fEs > 3 Mc for the hours 18^h00^m - 06^h00^m. Figure 2 presents their variation, in a semi-logarithmic plot, with the corresponding twelve-month running averages of sunspot number. The data for the period comprising most of the past declining period of solar activity exhibit a nearly linear relationship, so that the log of the ratio of percentage of total time of occurrence of fEs > 3 Mc at any two times is inversely proportional to the difference between the sunspot numbers at these times. This trend was used for the prediction of maximum usable reflection frequencies by sporadic-E ionization during the latter part of the past solar cycle [see "References" at end of paper, INTERSERVICE RADIO PROPAGATION LABORATORY, 1943]. Departure from this trend during the rising part of the past cycle of solar activity, as well as during the present rising cycle, indicates, however, that sunspot number may not be the variable associated with solar activity which bears the closest relationship to fEs variations.

The variation of the 12-month running-average value of the percentage of total time of occurrence of fEs > 3 Mc with smoothed values of sunspot latitude for sunspots of the last cycle is presented in Figure 3. (Values of average sunspot latitude through December 1938 from Greenwich Observatory, as published in the Monthly Notices of the Royal Astronomical Society, and subsequent values computed from Mount Wilson Observatory data, as published in the Journal of the Astronomical Society of the Pacific, were plotted against time; values presented here were read off the smooth curve drawn approximately through the mean of these.) Very little variation occurs in the prevalence of fEs > 3 Mc until the heliographic latitude of the regions of pronounced solar activity lies below about 11°.6. From this latitude, there is a pronounced increase in prevalence of fEs > 3 Mc with decreasing heliographic latitude of the sunspot belts, which amounts to a

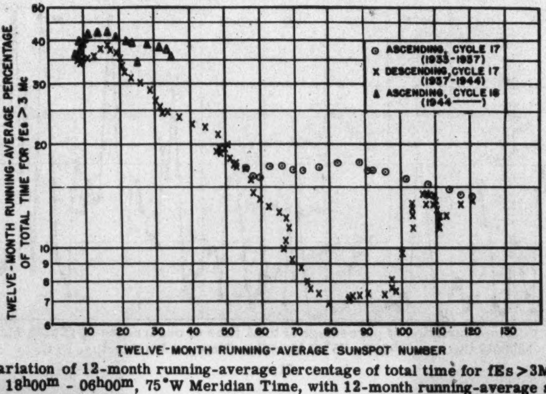


Fig. 2--Variation of 12-month running-average percentage of total time for fEs > 3Mc, at Washington, D. C., 18^h00^m - 06^h00^m, 75°W Meridian Time, with 12-month running-average sunspot number

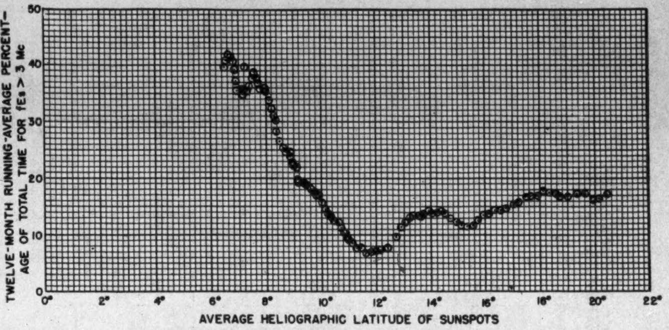


Fig. 3--Variation of 12-month running-average percentage of total time for fEs > 3Mc, at Washington, D. C., 18^h00^m - 06^h00^m, 75°W Meridian Time, with average heliographic latitude of sunspots

change in percentage of total time of occurrence of fEs > 3 Mc of seven per cent per degree of heliographic latitude.

The seasonal change in prevalence of Es ionization or "monthly index," may be expressed by the ratio of the monthly average to the 12-month running-average percentage of total time of occurrence of fEs > 3 Mc. The average values of monthly index over the entire period of observations are presented in Figure 4. As already indicated by the data shown in Figure 1, maximum values occur during the solstitial months of June and December, the June maximum being the greater, with minima during the equinoctial months of March and September. The change from June to December represents a change with solar declination, but the solstitial-equinoctial change

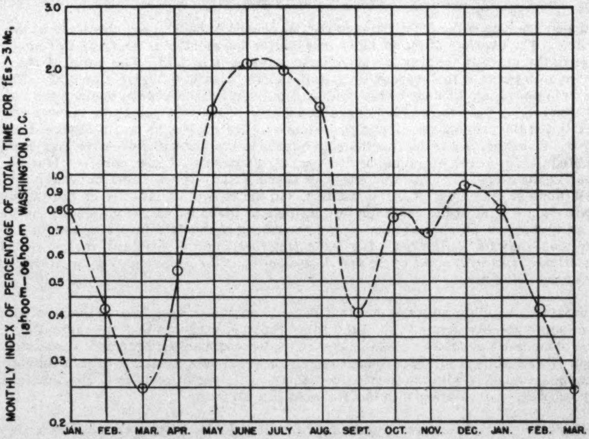


Fig. 4--Variation of monthly index of percentage of total time of occurrence of fEs > 3 Mc, 18^h00^m, 75°W Meridian Time, Washington, D. C.

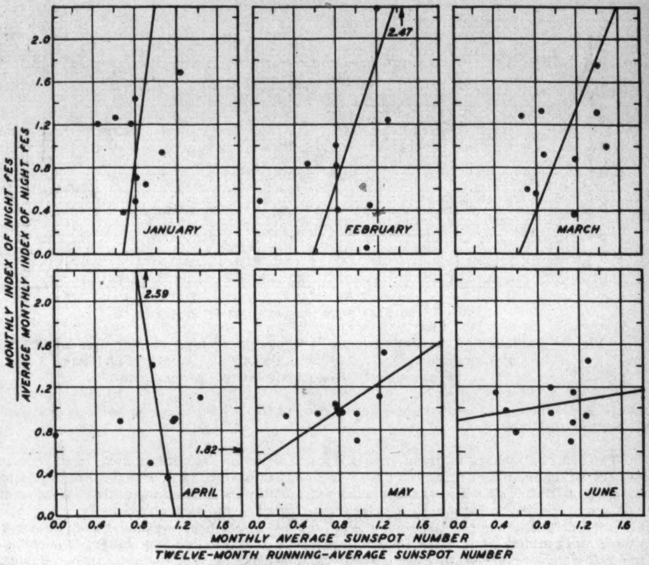
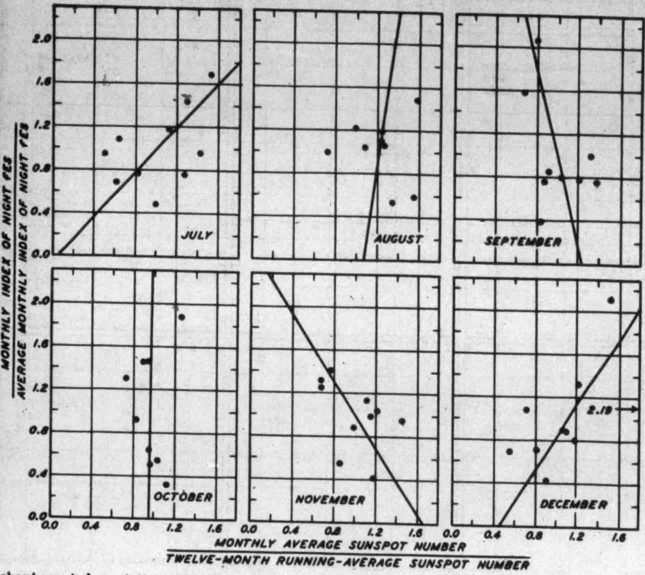


Fig. 5--Correlation between short-period variations in fEs and

suggests dependence upon the solstitial-equinoctial change of heliographic latitude of the center of the solar disc. The average of the monthly indexes for the months of June and December is 1.52; the average of the monthly indexes for March and September is 0.33. The ratio of the average equinoctial-month index to the average solstitial-month index is 0.33/1.52, or 0.22. The average difference in heliographic latitude of the center of the solar disc between equinoctial and solstitial months is about 6°.1. The range of heliographic latitude of the sunspot belts throughout which there is exhibited the pronounced rise in prevalence of fEs > 3 Mc, shown in Figure 3, is not as great as this. However, if one applies the above ratio to the low value of seven per cent, for the sunspot latitude 11°.6, at the beginning of this period, a value of 32 per cent is obtained for the heliographic latitude 6°.5, provided that one may assume equivalence in effect between the seasonal change of latitude of the center of the solar disc, and the change of latitude of the sunspot belts. This is about 64 per cent of the value for this latitude as given by extrapolation of the curve of Figure 3, an agreement which, considering the roughness of the data involved, and the nature of the assumptions, may be considered a fair indication that both the seasonal variation and long-period variation of fEs with solar cycle are dependent upon the distance of solar active areas from the center of the solar disc.

This behavior, together with the fact that there is an abrupt rise in prevalence of Es ionization for cases of solar activity within 11°.6 of the solar equator, suggests that sporadic-E-layer ionization may be principally caused by radially emitted solar corpuscles, probably associated with the solar corona [CHAPMAN, 1931-32]. Unfortunately, coronal data available at this time are too few to correlate quantitatively with the long-period solar-cycle variation of fEs, and too fragmentary to give any but rough correlation with the seasonal fEs variation.

It is interesting that the curve of seasonal variation of fEs, Figure 4, presents a very smooth change between the months of December and July, inclusive, but that the values of monthly index for August, October, and possibly November, are in excess of those which would be given by a similarly drawn smooth curve through points for these months. Standard errors for the values of average monthly indexes, beginning with that for January, are, respectively, 0.10, 0.10, 0.03, 0.11,



short-period variations in solar activity, Washington, D. C.

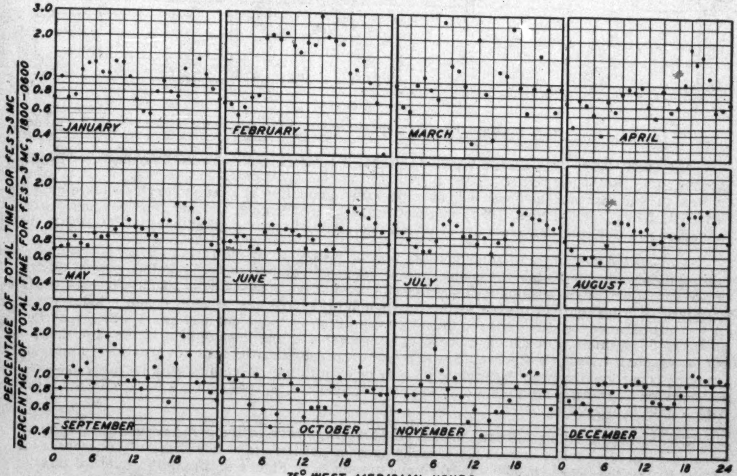


Fig. 6--Diurnal variations of ratio of percentage of total time for fEs > 3 Mc to that for hours $18^{h}00^{m}$ - $06^{h}00^{m}$, 75°W Meridian Time, at Washington, D. C.

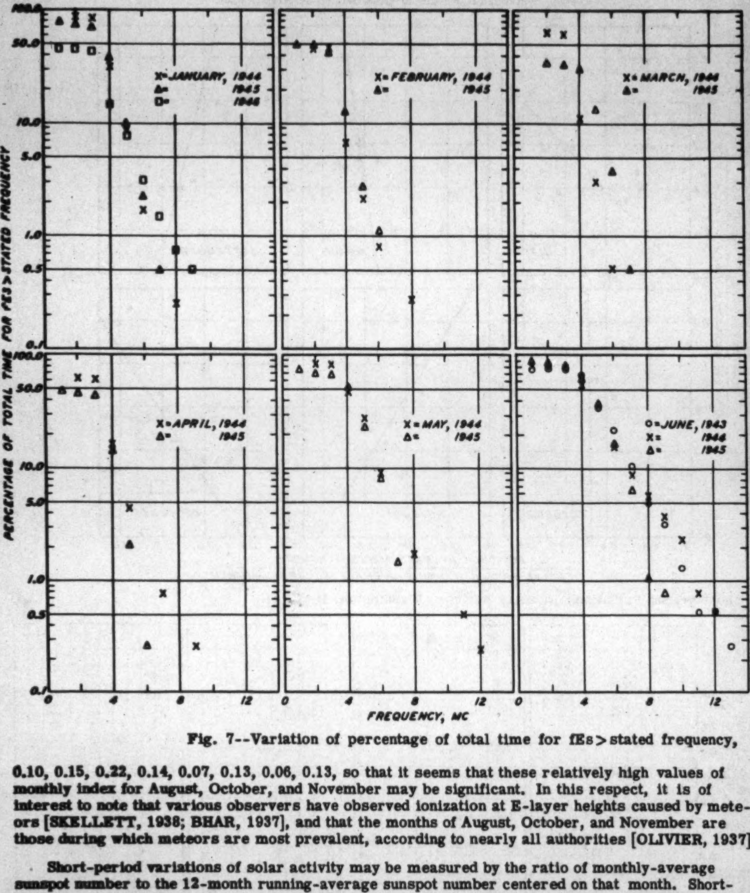
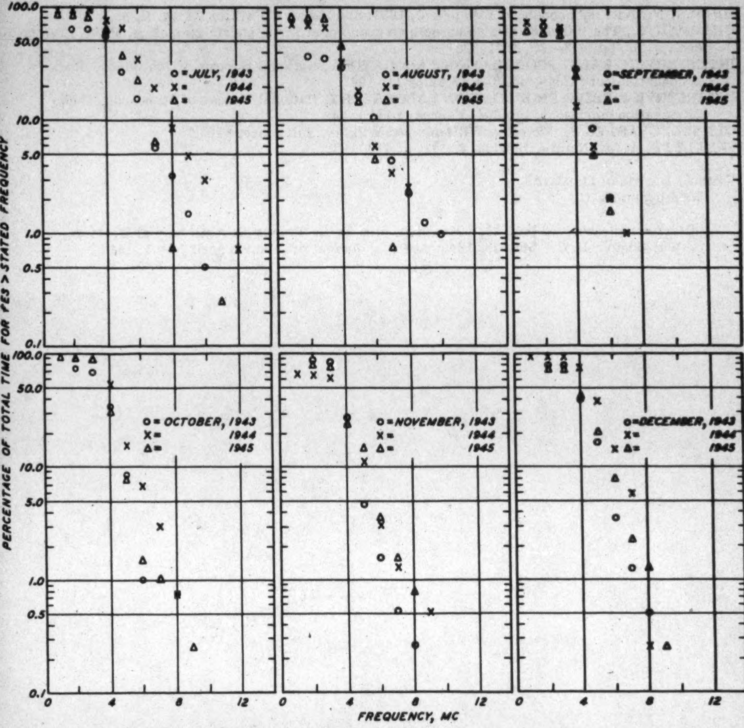


Fig. 7--Variation of percentage of total time for fEs > stated frequency,

0.10, 0.15, 0.22, 0.14, 0.07, 0.13, 0.06, 0.13, so that it seems that these relatively high values of monthly index for August, October, and November may be significant. In this respect, it is of interest to note that various observers have observed ionization at E-layer heights caused by meteors [SKELLETT, 1938; BHAR, 1937], and that the months of August, October, and November are those during which meteors are most prevalent, according to nearly all authorities [OLIVIER, 1937].

Short-period variations of solar activity may be measured by the ratio of monthly-average sunspot number to the 12-month running-average sunspot number centered on that month. Short-period variations of fEs may be measured by the ratio of the monthly index of the percentage of total time of occurrence of fEs > 3 Mc for any month to the average value of monthly index for that month. The correlation between these two quantities is rough, as may be seen by inspection of Figure 5, in which these data are presented, together with the lines of best fit for the points, but the seasonal trend of the correlation from direct proportionality near the solstices, to slight inverse proportionality near the equinoxes, may be significant. Beginning with January, the coefficients of correlation for each month are, respectively, 0.17, 0.52, 0.33, - 0.08, 0.52, 0.35, 0.49, 0.15, - 0.39, 0.01, - 0.38, 0.51.

The diurnal variation, for each month, of the average ratio of the percentage of total time of occurrence of fEs > 3 Mc, at each hour, to the average percentage of total time of occurrence of fEs > 3 Mc for the hours $18^{h}00^{m}$ - $06^{h}00^{m}$ are presented in Figure 6. Daytime values of this ratio are of doubtful significance, as previously noted, because of the masking effect of regular



with frequency, 18h00m - 06h00m, 75°W Meridian Time, Washington, D. C.

E-layer reflections, and because of ionospheric absorption. Values for equinoctial months are poor because of scanty data during these months.

Inspection of these diurnal variations, especially for summer months, when the data are better because of the greater prevalence of Es ionization, indicates that generally there appear both morning and evening maxima, and frequently a pre-sunrise minimum value. Allowing for the effects of regular E-layer masking and daytime absorption, these curves thus suggest that the true diurnal trend of fEs may be somewhat like the diurnal curve of F2-layer critical frequencies--a characteristic noted in Es data from several stations at lower latitudes.

The logarithm of the percentage of total time of occurrence of fEs, in excess of a given frequency, is approximately inversely proportional to that frequency, for frequencies above about three Mc, where the effects of regular E-layer masking, and of absorption, are not great, as may be seen from Figure 7. This decrease of percentage of time of occurrence with increased frequency is more rapid for equinoctial than for solstitial months. Knowledge of this relationship [INTERSERVICE RADIO PROPAGATION LABORATORY, 1943 and 1944] has been of considerable practical advantage in estimation of the probability of successful radio transmission in cases where transmission was only possible by means of Es reflections, and in determining the probability of interference or interception on high frequencies.

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INTERNAL WAVES IN THE OCEAN

C. W. Ufford

(This work represents some of the results of research carried out by the University of California Division of War Research under contract with the Office of Scientific Research and Development, Section 6.1; National Defense Research Committee; and with the Bureau of Ships, United States Navy Department.)

Abstract--Several sets of temperature measurements both from surface ships and submarines show that internal waves exist in the ocean with periods shorter than those heretofore observed. The waves with a period of one to two hours have heights up to 100 feet, and those with periods of the order of ten minutes have heights up to 20 feet.

Introduction--If two superposed liquids of different density have a common boundary, oscillations of this boundary may be set up which are known as internal waves in the liquid. In the ocean, such a boundary might be caused by a difference of temperature or by a difference in salinity. The greatest difference of temperature will occur at the thermocline, which is often a layer in which there is a sharp negative temperature gradient underlying a surface layer of isothermal water. One would then expect internal waves to be formed in the thermocline. As the difference in density is small, little energy will be required to start and maintain this wave motion. The surface waves, on the other hand, require 30,000 times as much energy because of the greater difference in density between the air and water at the boundary. The energy for the internal waves could come from the surface waves, especially when they break, or from currents in the ocean.

Internal waves can be formed not only at a boundary where the density changes discontinuously, but also in water in which the change is continuous. There are no internal waves in homogeneous water in which the density does not change with depth. That internal waves are present in the ocean has been proved by measuring the variation with time of the temperature, salinity, and oxygen content at various depths. Before the War, measurements were made in a series with sample bottles and reversing thermometers from an anchored or slowly drifting ship. As each lowering required an appreciable time, there was a time interval of more than one hour and sometimes as much as two hours between successive lowerings. This meant that only long-period waves could be found by these methods.

The information on internal waves found in this way available up to 1942 is given by SVERDRUP, JOHNSON, and FLEMING [see "Reference" at end of paper, 1942]. Waves with periods of 24 and 12 hours, corresponding to the periods of the tides, and with heights as great as 300 feet were found. There was some evidence for waves with shorter periods, but the periods found by this method had to be at least as large as the interval of one to two hours between successive lowerings.

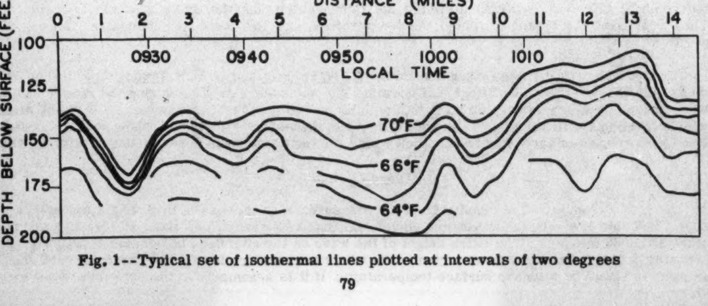

Fig. 1--Typical set of isothermal lines plotted at intervals of two degrees

Table 1--*Internal waves.*

Date	Speed of ship	Time between crests	Height 2 × amplitude	Sea state[a]	Depth to bottom of mixed layer	
					Minimum	Maximum
	knots	min	ft		ft	ft
October 14, 1943	13	9	12	2	105	171
		110	66			
December 11, 1943	4	12	12	4, 5	345	400
December 12, 1943	4	8	12	4	325	395
December 21, 1943	13	9	6	5	265	315
		90	48			
December 22, 1943, a. m.	13.1	18	18	5	205	275
		88	64			
December 22, 1943, p. m.	13	12	18	5	120	275
		110	142			

[a] Instruction to Marine Meteorological Observers, United States Department of Commerce,

In order to find out whether there were any waves of shorter period, it was necessary to make lowerings in much more rapid succession. For this purpose the bathythermograph, which gives a continuous record of temperature as a function of depth, has provided a greatly superior instrument.

The evidence for internal waves in the ocean rests on periodic changes found in the temperature, salinity, or oxygen content at a fixed position and depth. Periodic changes in depth caused by internal waves have been observed by submarines when balanced in the thermocline. Bathythermograph readings taken by submarines occasionally show different temperatures at the same depth, one when diving, the other when rising. The waves indicated by these changes have periods varying from the diurnal and semi-diurnal periods of the tides to some as short as a few minutes.

Description of experimental procedure--The first type of evidence for internal waves consists in showing a periodic change in temperature at constant depth that would be caused by the periodic rise and fall of the thermocline or any other water in which a temperature gradient existed. During cruises of the U. S. S. *Beaumont* in the mid-Pacific north of the Hawaiian Islands, bathythermographs were taken at intervals of five minutes or less for one to four hours on October 14, 1943, and several days in December 1943. A deep and a shallow bathythermograph were used. The cruises were made in the open sea under supposedly isothermal conditions. Six of the eleven groups of slides were studied as representative.

From the bathythermograph slides, isothermal lines were plotted at intervals of two degrees. A typical set of these lines is shown in Figure 1. The ordinates give the depth at which the temperature had the particular value shown for each curve. The abscissa gives the time at which the bathythermographs were taken and is also proportional to the distance the ship had moved in the case of the U. S. S. *Beaumont*, which was moving with constant velocity. The curves do not represent the depths at which the temperature had the same value at a single fixed position nor the depth at different positions at which the temperature was the same at a single instant. They represent the depths at which the temperature was the same at successive times and positions.

Bathythermographs were taken aboard the *E. W. Scripps* and U. S. S. *Democracy* during cruises in the waters off San Diego, California. The ships were drifting during the readings, which were spaced at intervals varying from half an hour to two minutes. Isothermal lines were drawn which, if the unknown velocity of the ship relative to the water is neglected, show how at a position fixed with respect to the water the depth at which the temperature is constant varies with the time.

Presentation of data

U. S. S. Beaumont--The results from the measurements aboard the U. S. S. *Beaumont* are shown in Table 1, where the waves are seen to fall into two groups, one about 12 feet high and the other about 60 feet high. The extra height of the wave on the afternoon of December 22, 1943, is probably not real, but came from a rise in the whole temperature level along the course of the ship, as is shown by a higher surface temperature. If it is assumed that the periods are not much

U. S. S. Beaumont

Character of the gradient in the mixed layer			Wind force	Bathythermograph interval
Number of cases of slight negative	Number of cases of slight positive	Number of cases of isothermal water		min
1	18	14	3, 4	3
2	6	10	3, 4	4
5	5	8	4, 5	4
3	14	10	6, 7	5
9	12	16	5, 6	5
0	3	9	7	5

Circular M, June 1941, gives the scale of sea state.

different from the times from crest to crest, the low waves have a period of about ten minutes, and the high ones one to two hours.

The results in Table 1 were taken from graphs similar to Figure 1, in which the layer depth has been plotted against the time. The average time that the ship took to pass from one wave crest to the next was measured directly from the graphs and is listed in Table 1. The height of the waves was measured from the tangent to successive crests and troughs and the average entered as the height in Table 1. Finally, Table 1 gives a summary of the pertinent oceanographic conditions under which the bathythermographs were taken. It was windy and rough, which meant a deep mixed layer of isothermal water at the surface.

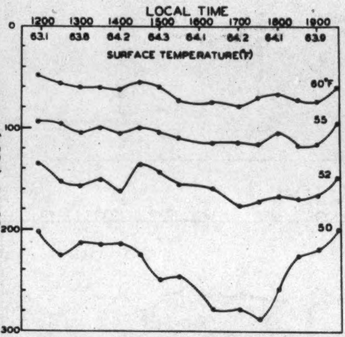

Fig. 2--Plot of data from measurements obtained aboard the *E. W. Scripps* and the U. S. S. *Democracy*

E. W. Scripps and U. S. S. Democracy--The results obtained from the measurements aboard the *E. W. Scripps* and U. S. S. *Democracy* are shown in Table 2. The bathythermographs were lowered in each instance while the ship was drifting. The first entry is taken from the data plotted in Figure 2, where a period of about an hour is superposed on a longer period that is probably a semi-diurnal wave of tidal period. The bathythermographs did not extend over a long enough time to give the period of the longer wave accurately. As the bathythermographs were taken at half-hour rather than few-minute intervals, the one-hour period of the shorter period waves is uncertain, but of the same order of magnitude as the longer period waves observed by the *Beaumont*. The short waves found by the *Beaumont* would not appear here because the interval between bathythermograph lowerings was too long to reveal them. A similar hourly period was found on August 28 and 29, 1944.

The other entries in Table 2 are for waves found by bathythermograph lowerings with an interval of two, three, or five minutes. These show several instances of waves with a period of ten to 15 minutes. A typical example of the waves observed aboard the U. S. S. *Democracy* is shown in Figure 3, where the depths of the isotherms are plotted against the time. The time between crests and the heights of the waves listed in Table 2 were read by inspection from graphs similar to Figure 3.

Figure 4 shows the result of an attempt to measure the longer period of the waves more accurately by observations extended over a longer time. The sequence includes two sets of short-interval bathythermographs which appear as a group of points on this scale, through which the curve has been extended by averaging the curve over half-hour intervals. Although the curve is irregular, a period of about an hour is indicated.

Table 2--Internal waves, E. W. Scripps and U. S. S. Democracy

Date	Time between crests	Height 2 × amplitude	Bathythermograph interval
	min	ft	min
	E. W. Scripps		
June 7, 1943	62	7	30
August 28, 1944, a. m.	10	6	3
	9	6	5
August 28 - 29, 1944	67	5 - 20	30
	U. S. S. Democracy		
September 1, 1944, a. m.	14	3	5
	36	4	
September 1, 1944, p. m.	18	3	5
	52	5	
September 2, 1944	12	3	3
	120	12	
September 3, 1944, a. m.	13	3.5	2
	61	10	
September 3, 1944, p. m.	17	3	2
September 4, 1944	14	5	3
	100	10	
September 5, 1944	13	3	5

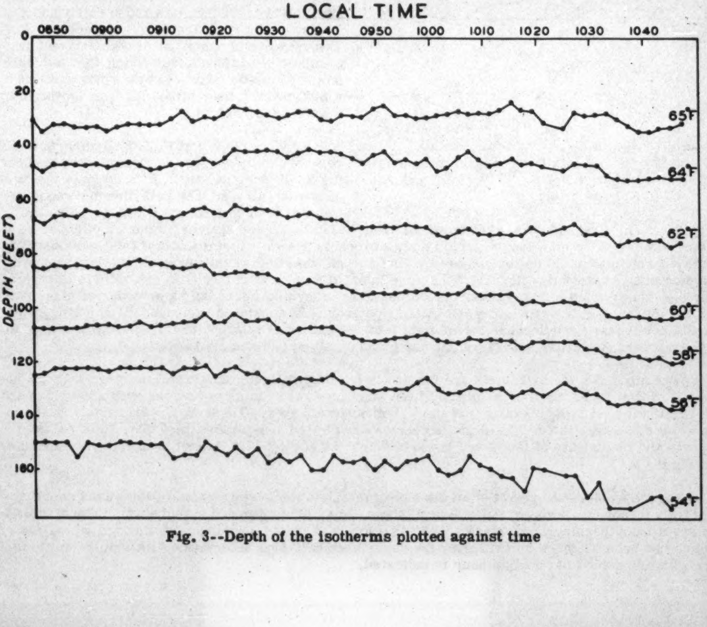

Fig. 3--Depth of the isotherms plotted against time

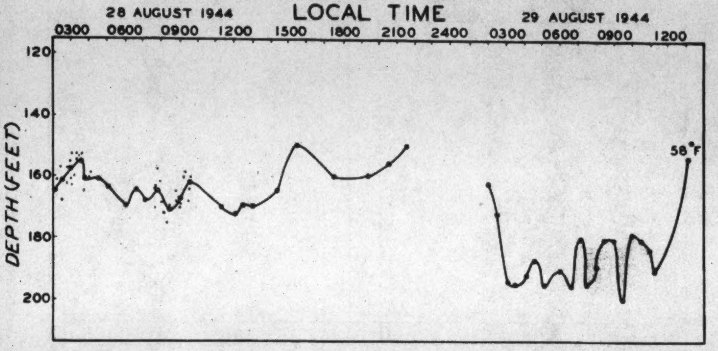

Fig. 4--Results of wave measurements by observations extended over longer periods of time

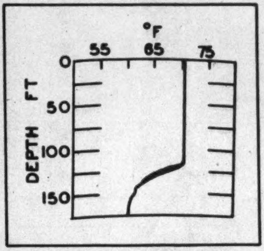

Fig. 5--Bathythermograph trace showing the thermal conditions typical of Figure 1

Figures 5 and 6 show representative bathythermograph traces from which the isotherms of Figures 1 and 3, respectively, were plotted. Figure 5 is typical of the deep mixed layer, 122 feet, of isothermal water overlying a thermocline found in mid-ocean. Figure 6, on the other hand, shows the type of shallow, 23 feet, mixed layer found off San Diego, California.

U. S. S. Aspro--The second type of evidence for the existence of internal waves comes from the periodic rise and fall of a submarine balanced in the thermocline. Two sets of measurements conducted by Redfield and Bumpus aboard the U. S. S. Aspro showed this effect: In the first set the depth of the thermocline fluctuated by ten to 15 feet; in the second, while balancing in the thermocline, the keel depth fluctuated from 54 to 66 feet with a regular period of 14 to 16 minutes. Both of these observations indicate the presence of internal waves with a height of about 12 feet. During the second set there was no indication of progressive sinking or rising which might have been caused by soaking up, leakage, or cooling. The waves of the first set are pictured in Figure 7, which shows clearly their periodic character with a period of about 15 minutes. The tests were made in the submarine test area off Portsmouth, New Hampshire, on September 6 and 7, 1943,

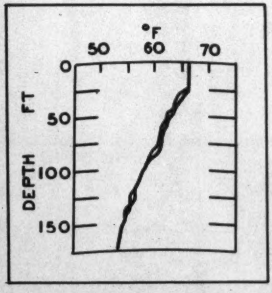

Fig. 6--Bathythermograph trace showing the thermal conditions typical of Figure 3

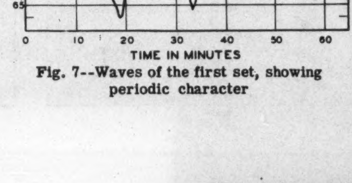

Fig. 7--Waves of the first set, showing periodic character

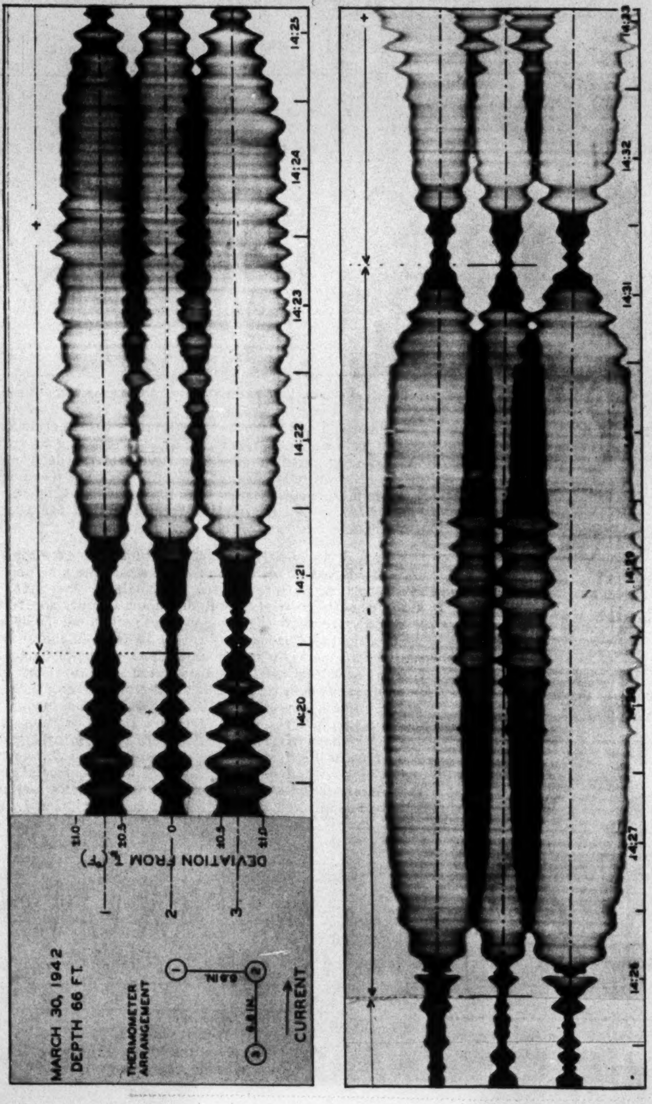

Fig. 8--Temperature variations at three fixed points, characteristic of internal waves

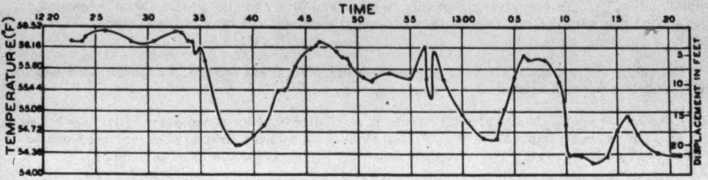

Fig. 9--Data taken from the record of one thermometer at a depth of 70 feet two hours before the data of Figure 8

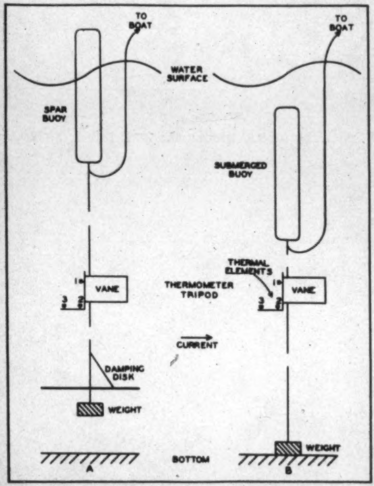

Fig. 10--Method of taking measurements shown in Figures 8 and 9

when the thermocline was found to be 20 feet thick after a moderately strong easterly wind had been blowing for five days. In contrast to the method of bathythermographs that measures only the time between crests, a submarine measures the actual period of the waves.

Early experiments at the University of California Division of War Research--The third type of evidence for internal waves, from a series of experiments performed by Munk, is similar to the first in that the periodic change of temperature at a fixed depth is measured, but in this case with a rapid-response thermometer either attached to a buoy or anchored to the bottom rather than with a bathythermograph. A typical oscillograph is shown in Figure 8, where the thickness of the envelope is a record of the temperature of three thermometers spaced as shown at the left of the Figure. The slower fluctuations have a period of 5.5 minutes and represent internal waves. Similar waves were found on other records with periods from five to 15 minutes. Thus in all three cases of short-interval observations: With bathythermographs lowered from surface ships, the Aspro, and Munk's experiments, an internal wave with a period of the order of ten minutes was found. The bathythermographs lowered every 30 minutes on the E. W. Scripps were spaced too far apart to show this period. There is evidence to show that the fluctuations in Figure 8 with a shorter period of 12 seconds appearing at the limits of the envelope, are caused by surface waves.

Another way of presenting the results of Munk's experiments is shown in Figure 9, which was taken from the record of one thermometer at a depth of 70 feet two hours before the data of Figure 8. It shows a fluctuation of temperature of ten minutes period and approximately 1°.7 F range. A bathythermograph taken simultaneously gave an average gradient of 0°.107 F/ft at 75 feet depth. Figure 9 thus represents an internal wave of 1°.7 F/0°.107 F/ft = 16 feet height.

The measurements shown in Figures 8 and 9 were taken off San Diego, California, on March 30, 1942, at a depth of about 65 feet. Three thermometers were clamped to a cable which was attached to a spar buoy above and to a damping disk and heavy weight below as in Figure 10A. The cable between the ship and the spar buoy was kept slack. In this way the vertical motion of the thermometers caused by the waves and the ship was greatly reduced. To eliminate the motion of the thermometers entirely for some experiments, the spar buoy was completely immersed by a heavy weight on the bottom of the ocean as in Figure 10B. This required that the ship be anchored in deep water, a difficult and time-consuming operation possible only under favorable weather conditions. The arrangement of the thermometers is shown at the left of Figure 8. The thermometers were of the resistance type designed by Kalbfell, with recording by a Westinghouse oscillograph. The thickness of the envelope in Figure 8 measures the difference in temperature from an arbitrary balance point, T_b. Temperatures above T_b are marked plus over the graph, those below minus. The record represents a continuous trace of temperature against time at three points fixed in space.

In conclusion, evidence has been presented which shows that internal waves with periods as short as a few minutes exist in the ocean.

Acknowledgments--It is a pleasure to thank A. C. Redfield for permission to include his work with D. F. Bumpus on internal waves. Walter Munk, who was the first to observe short-period internal waves, has generously given permission for his experiments to be included here.

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INTERNAL WAVES MEASURED AT THREE STATIONS

C. W. Ufford

(This work represents some of the results of research carried out by the University of California Division of War Research under contract with the Office of Scientific Research and Development, Section 6.1; National Defense Research Committee; and with the Bureau of Ships, United States Navy Department.)

Abstract--Series of measurements of the depth of an isothermal layer made with bathythermographs or thermocouples simultaneously at three stations indicate strongly the existence of internal waves in the ocean. The properties of the internal waves found in this way are: (1) The wave length is of the order of a few hundred yards; (2) the shorter periods are of the order of a few minutes up to a few hours; and (3) the speed in all cases observed thus far is less than one knot.

Introduction--In another paper [see "References" at end of paper, UFFORD, 1947] strong evidence has been given to show that internal waves of periods as short as a few minutes exist in the ocean. One of the first questions that arises is whether the waves are of the progressive or standing type. Furthermore, what period, wave length, and velocity do they have? To answer these questions it is necessary to measure the displacements caused by the waves simultaneously at more than one station. When this was done at first with three stations on one ship it was found that the waves at the three stations were almost in phase. Therefore, in order to get more difference in phase, three ships were used spaced at the corners of a triangle about 1000 feet on a side. The measurements were made with bathythermographs and the depth of an isothermal surface plotted as a function of the time at each of the three stations. The temperature was also measured at three stations by thermocouples at the corners of a triangle spaced 500 or 1000 feet on a side, and recorded aboard a single ship.

Theory

Calculation of the properties of internal waves from observations at three stations--The purpose of these theoretical considerations is to make it possible to find the characteristics of internal waves; period, wave length, and velocity, from simultaneous measurements, either of the depth of an isothermal surface as it varies with the time at three stations, or of the temperature measured at three fixed points. To obtain the desired properties of the waves, it is necessary to read the time from crest to crest of the waves and their relative phases at the three stations from the depth of the isothermal surface or from the temperature curves.

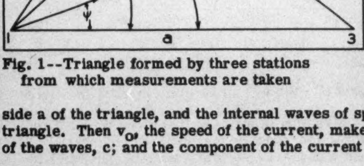


Fig. 1--Triangle formed by three stations from which measurements are taken

The three stations from which measurements are taken are assumed to be stationary, and the waves and the current to pass underneath. The time between the passage of one wave crest and the next under a ship would be equal to the period if there were no current. Owing to the current, this time is decreased if the current is in the same direction as the direction of propagation of the waves; and increased if the current is opposite to the waves. Let the triangle formed by the three stations be laid out as in Figure 1. The sides 1-3 and 1-2 of the triangle are, respectively, a and b, and φ is the angle between these two sides. Let the speed of the current, v_0, make an angle ψ with the side a of the triangle, and the internal waves of speed c make an angle θ with the side a of the triangle. Then v_0, the speed of the current, makes an angle $\theta - \psi$ with the direction of propagation of the waves, c; and the component of the current in the direction of the waves will be

$$v = v_0 \cos(\theta - \psi) \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Now the measured time from crest to crest, t_o, and the velocity of the waves with respect to the ship must vary in such a way as to give the wave length:

$$\lambda = t_o \left| c + v \right| = t_o \left| c + v_o \cos(\theta - \psi) \right| \tag{2}$$

where c is the speed of the waves. Cos $(\theta - \psi)$ gives the proper change in sign when $(\theta - \psi) > 90°$, that is, when the relative velocity of the ship and wave becomes the difference of the speed of the wave and the speed of the current parallel to the wave.

The period of the wave is

$$T = \lambda / c \tag{3}$$

If the waves are assumed to be sinusoidal, and if the origin of time be chosen at that instant at which the displacement of the wave is zero, at point 1 in Figure 1, and increasing; then the displacement at point 1 at any future time, t, is given by

$$s_1 = s \sin 2\pi(t/t_o) \tag{4}$$

and those at the points 2 and 3 by

$$s_2 = s \sin 2\pi[t - t_{(1-2)}]/t_o \tag{5}$$

$$s_3 = s \sin 2\pi[t - t_{(1-3)}]/t_o \tag{6}$$

where, to recapitulate, s is the amplitude of the wave assumed to be the same at all three points, s_i is the displacement at the point $i = 1, 2, 3$, t_o is the time between crests, $t_{(1-2)}$ is the time for the wave to travel from point 1 to point 2, and $t_{(1-3)}$ is the time for the wave to travel from point 1 to point 3. These latter times are obtained by reading from the isothermals, the difference in the time at which a given phase of the wave appears at the two points in question.

First θ, the angle between the direction of propagation of the wave and the side of the triangle, will be found. The differences of phase in (5) and (6) between the two points may be expressed in terms of the distance between the points measured along the direction of propagation of the waves by

$$-[2\pi t_{(1-2)}]/t_o = -[2\pi b \cos(\varphi - \theta)]/\lambda \tag{7}$$

$$-[2\pi t_{(1-3)}]/t_o = -(2\pi a \cos\theta)/\lambda \tag{8}$$

where a and b are the sides of the triangle opposite the points 2 and 3, respectively, φ is the angle of the triangle at the point 1, θ is the angle that the direction of the internal wave makes with the side a of the triangle, and λ is the wave length. Next divide (7) by (8).

$$t_{(1-2)}/t_{(1-3)} = [b \cos(\varphi - \theta)]/a \cos\theta \tag{9}$$

Then

$$\cos(\varphi - \theta) - [a t_{(1-2)}/b t_{(1-3)}] \cos\theta = 0 \tag{10}$$

$$\cos\varphi \cos\theta + \sin\varphi \sin\theta - [a t_{(1-2)}/b t_{(1-3)}] \cos\theta = 0 \tag{11}$$

and finally

$$\tan\theta = \left\{ [a t_{(1-2)}/b t_{(1-3)}] - \cos\varphi \right\} / \sin\varphi \tag{12}$$

Equations (8) and (12) together determine the quadrant in which θ lies; for example, when both $t_{(1-2)}$ and $t_{(1-3)}$ are positive and $a t_{(1-2)}/b t_{(1-3)} > \cos\varphi$, $\cos\theta$ is positive, $\tan\theta$ is positive, and θ is in the first quadrant. It is usually simplest to arrange the triangle of Figure 1 so that θ is actually in the first quadrant.

Now that θ has been found, (8) will give λ,

$$\lambda = (a t_o \cos\theta)/t_{(1-3)} \tag{13}$$

The speed will then be given by (2).

$$c = (\lambda / t_o) - v_o \cos(\theta - \psi) \tag{2}$$

If c as given by (2) is negative, the waves travel in a direction opposite to that given by θ. The speed of the current under the ship, v_o, and ψ, its direction, must be measured experimentally. In the experiments using bathythermographs the current was measured with a current pole, and in those using thermocouples with the Sverdrup-Dahl photoelectric current meter. Finally, (3) will give the period since now both the wave length, λ, and the speed, c, are known.

Presentation of the data

Bathythermographs--The data to be presented here were taken aboard the E. W. Scripps on November 29, 1944, and aboard the YAG-6, PYC-13, and E. W. Scripps on March 6, 1945. On November 29, 1944, bathythermographs were lowered every two minutes from three positions aboard the E. W. Scripps; the bow, the waist, and the stern, during an interval of 3.5 hours. The depth of the isothermal layer of temperature 57°.7 F at the three stations during the whole interva is shown in Figure 2. There is seen to be a smoothing out of the curve after 15^h00^m, and then a uniform oscillation of the layer that is reproduced on a larger scale in Figure 3. The curves are mathematical sine curves that have been fitted to the observed points which made it possible to determine the relative phases of the waves at the three stations. In the earlier interval before 15^h00^m, the curves are too irregular to determine definite phase relations, and so this interval was not used in the analysis. The order in which the three curves in Figure 3 progress indicates that the waves came from the direction in which the ship was heading and struck first the bow, then amidships, and finally the stern. These phase relations are well maintained throughout the interval shown in Figure 3, and suggest that the waves are of the progressive type. A typical bathythermograph trace from which Figure 2 was plotted is shown in Figure 4.

Further confirmation of the presence of progressive waves is afforded by Figure 5, which was obtained from three ships anchored in 20-fathom water (see insert, Fig. 6). Four series of bathythermograph lowerings were made, two from the E. W. Scripps, bow and stern, and one each from the other two vessels. Lowerings were made at about two-minute intervals for a period of three hours. Thermal conditions were unfavorable. There was a small thermocline with a total temperature decrease of 0°.3 F, at a depth of 65 feet (see Fig. 7). Above and below the thermocline, the water was isothermal. The small difference of temperature was difficult to read accurately, and also made the wave velocity very small. The irregular character of the waves in Figure 5 makes it difficult to determine the phase differences. Therefore, a process of averaging was used in an effort to bring out the more obscure content of the data. The thermocline increased steadily in depth during the three-hour period of Figure 5, owing to the presence of waves of longer tidal period that were eliminated by subtracting them out. This left waves of a period shorter than the semidiurnal tidal waves, but longer than the shortest periods which were destroyed by the running averages used.

The periodic character of the average waves in Figure 6, although not as regular as that of Figure 3, is clearly evident. Also, the phase relations at the different stations stand out and

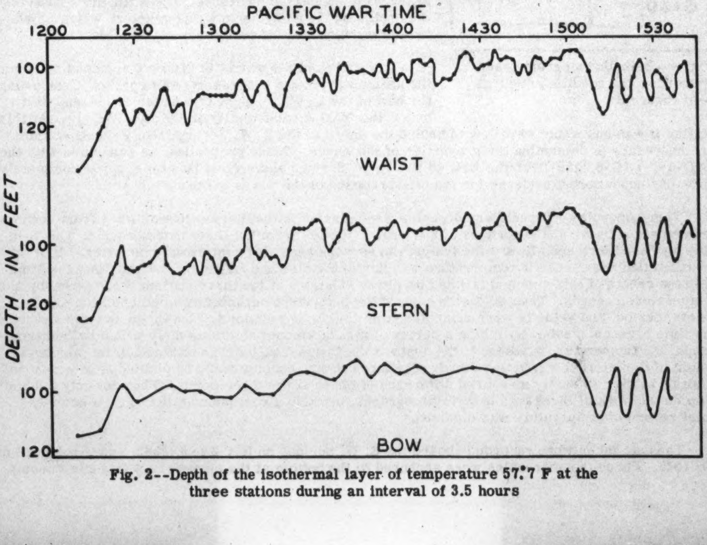


Fig. 2--Depth of the isothermal layer of temperature 57°.7 F at the three stations during an interval of 3.5 hours

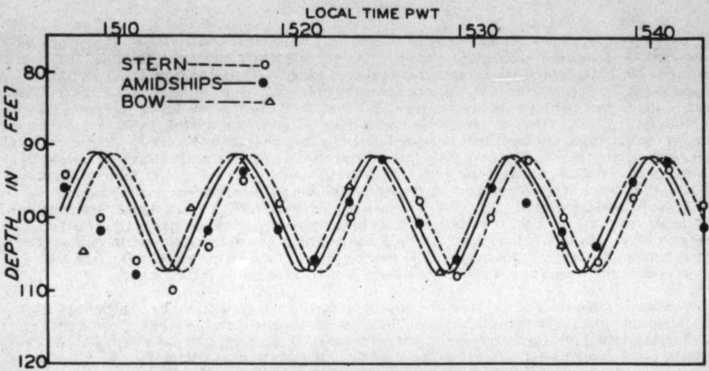


Fig. 3--Uniform oscillation of the isothermal layer

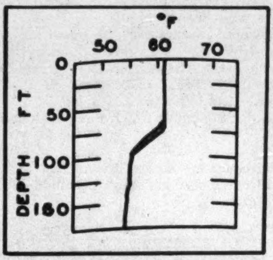


Fig. 4--Bathythermograph trace showing the conditions typical of Figure 3

maintain their relative positions throughout the interval shown. The waves at the bow and stern of the E. W. Scripps and at the YAG-6 have approximately the same amplitude and are displaced in phase as would be expected for progressive waves. At the PYC-13, the amplitude is about half that at the other ships, whereas it should be the same for a progressive wave. There was trouble with the bathythermograph aboard the PYC-13, and the first part of the measurements had to be made with a deep bathythermograph. However, even after the shallow bathythermograph had been repaired and put back into use at $09^{h}36^{m}$, the relative heights of the waves appeared unaltered. The difficulty of reading the depths on the bathythermograph trace at which small temperature decreases occur may explain this result.

The phases of the waves in Figure 6 are consistent with the assumption that a progressive wave passed first under the bow of the E. W. Scripps, then under the stern, next under the YAG-6, and finally under the PYC-13. At this station it was one whole wave length behind the phase at the E. W. Scripps. Only three stations are necessary to determine the properties of the waves. These properties, as calculated with the PYC-13, YAG-6, and first the bow of the E. W. Scripps and second the stern, agree completely, affording encouraging evidence for the interpretation of the waves given here.

Thermocouples--Three thermocouples were planted in the thermocline on lines from anchors to submerged buoys at the corners of a triangle. Cables from the three thermocouples ran to a ship anchored fore and aft, and the temperatures were recorded continuously on board. If it is assumed that the change in temperature was due to the rise and fall of the thermocline, the time between crests of this rise and fall and its phase relations at the three stations were given by the temperature records. Then, as in the case of the bathythermograph measurements, the wave length, period, and velocity were computed from the phase relations at the three stations and from the time between crests. By taking a series of measurements simultaneously with a bathythermograph, the temperature gradient at the depth of the thermocouples was obtained, from which the height of the internal waves was found. The three thermocouples could be planted at any desired position to give an easily measured difference of phase at the three points. Thus not only did one ship do the work of three with bathythermographs, but also a continuous rather than a point-to-point record of temperature was obtained.

The data taken were recorded aboard the E. W. Scripps on July 2 to 6, 1945, and October 16 to 19, 1945. Three thermocouples were anchored to the bottom at the corners of a triangle roughly

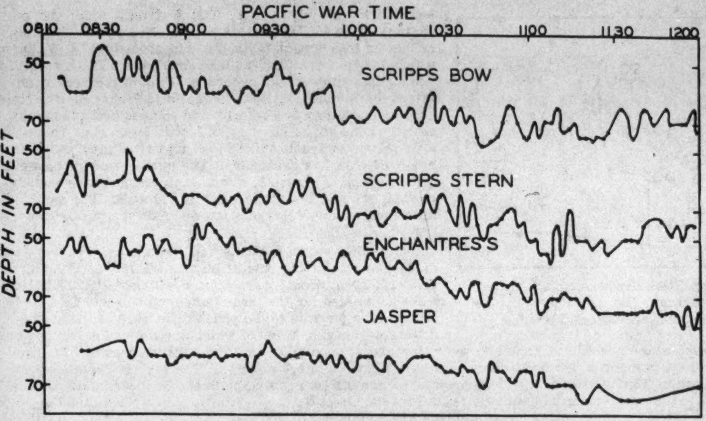


Fig. 5--Depth of thermocline measured at four stations, showing presence of progressive waves, March 6, 1945

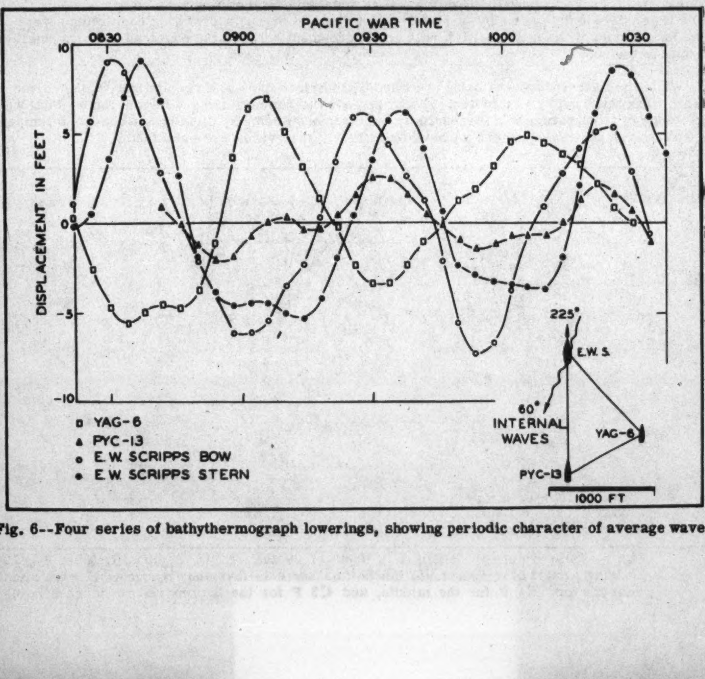


Fig. 6--Four series of bathythermograph lowerings, showing periodic character of average waves

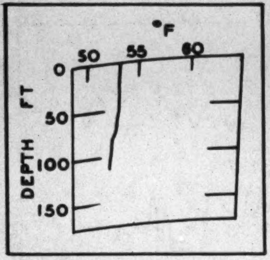


Fig. 7--Bathythermograph trace showing the conditions typical of Figures 5 and 6

equilateral, on July 2 to 6, 1000 feet on a side, and on October 16 to 19, 500 feet on a side. From each thermocouple an iron constantan cable lead aboard the E. W. Scripps, where the temperature was measured with a D. C. amplifier and an Esterline-Angus recorder. Part of the record obtained on October 17, 1945, is shown in Figure 8. The time scale was roughly 3/4 in/min, and was calibrated more exactly by pips on the chart at half-hour intervals. These pips also served to synchronize the charts after they had been removed from the recorders. The numbers of the corners of the triangle, Figure 1, where each temperature was recorded, are marked at the right of Figure 8. The small oscillations with a period of a few seconds are surface waves.

The differences in phase, $t_{(1-2)}$ and $t_{(1-3)}$, were found by inspection for the data of July 2 to 6, 1945. For October 16 to 19, 1945, cross correlation coefficients [REITZ, 1927] were calculated for the three temperature records and plotted as a function of the phase difference of the curves. A series of peaks, three of which are shown for each pair of temperature records in Figure 9, were obtained separated by the time between crests, t_o. The average value of t_o from the three curves in Figure 9 is 6.8 minutes. The highest central peaks shown in Figure 9 occur for the phase displacements corresponding to the best correlation. The three time displacements at these peaks give values of $t_{(1-2)} = 9.6$, $t_{(2-3)} = -1.6$, and $t_{(1-3)} = 8$ minutes. It is seen that these readings are consistent in that $t_{(1-2)} + t_{(2-3)} = t_{(1-3)}$. If the waves at the three stations were perfectly sinusoidal, all the peaks in Figure 9 would be of the same height, and the correlation method of finding the phase displacements would not work. However, these correlation coefficients proved of great advantage in determining phase displacements that were impossible to determine by inspection. Both inspection and correlation coefficients were used for the data of October 17, 1945, with good agreement between the phase differences obtained by the two methods.

While the temperature was being recorded by thermocouples at three stations, bathythermographs were taken every 15 minutes. The trace gave the temperature gradient at the depth at which the change of temperature was measured by the thermocouples. By dividing the change in temperature by the temperature gradient the heights of the internal waves were obtained.

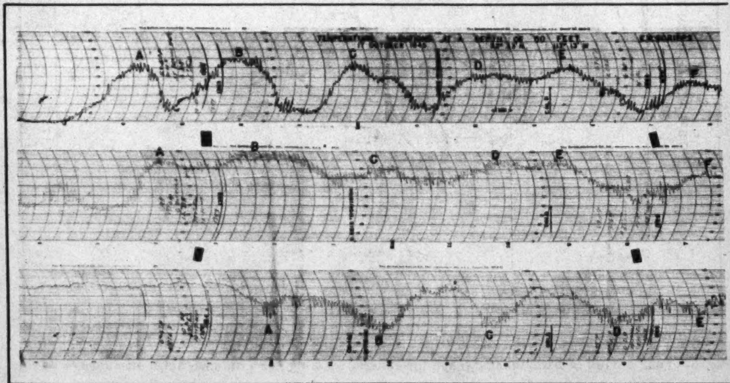


Fig. 8--Temperature variations at a depth of 50 feet, E. W. Scripps, October 17, 1945, a single crest of temperature; the bottom scale is inverted; horizontally each division for the top, 2°.1 F for the middle, and 4°.3 F for the bottom record corresponding to

Discussion and results

The results of the measurements are shown in Table 1. The height, period, wave length, and velocity of the waves are given, together with the position of the ship, state of the sea, and the depth of the water. The wave length on November 29, 1944, is not reliable because of the difficulty of measuring the difference in phase at the three stations. The curves are shown in Figure 3, where, owing to the smallness of the shift in phase, a small error in drawing the curves through the observed points would make a large error in the calculated wave length.

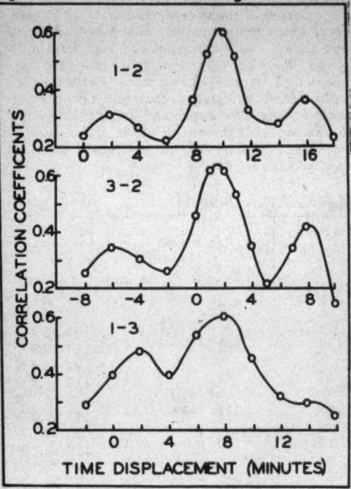
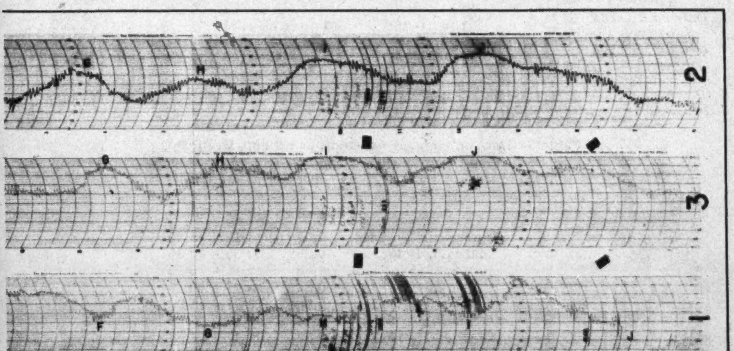


Fig. 9--Phase difference of the curves for the three temperature records

With a view to increasing the small phase difference found on November 29, 1944, three ships were used on March 6, 1945, to obtain a spacing sufficiently large for the waves to be definitely out of phase at the three stations. This was successful as is seen in Figure 6, in which the waves at the PYC-13 are a whole period behind those at the E. W. Scripps. Therefore, the value of the wave length is more reliable in this calculation than that on November 29, 1944. Moreover, as previously pointed out, only three stations are necessary to get the wave length. The wave length as calculated using the PYC-13, YAG-6, and first the bow of the E. W. Scripps and second the stern, differed by less than 0.6 per cent, which indicates that the results calculated from the phase difference at three stations on March 6, 1944, are consistent among themselves.

It should be emphasized particularly that the value of the direction of the line along which the waves move, but not the sense along this line, calculated from three stations depends



12^h30^m - 14^h00^m PST, position 32°33′N, 117°13′W; each letter marks the passage of represents one minute; full-scale deflection on the vertical scale represents 3.2 F stations 2, 3, and 1, respectively only on the phase differences $t_{(1-2)}$ and $t_{(1-3)}$ and the dimensions of the triangle, and not on the time between crests nor the magnitude of the current and its direction. The wave length depends in addition on the time between crests. As the difference of phase and the time between crests can be measured with some confidence, wave lengths given in Table 1 are more reliable than the other results. The current had to be averaged over the period of the measurements and was subject to fluctuation caused by the motion of the ship from which the meter was suspended. A small change in direction can often cause a large percentage change in the component of the current in the direction of the waves. When this component, $v_o \cos(\theta - \psi)$ of (2), is of the same size as λ / t_o, large errors in the speed, c, and hence in the period, T, from (3) can occur. The waves on October 18, 1945, for example, had a negative value of c which indicated a complete reversal in the direction of the waves. This also probably accounts for the slow speed and long periods found on October 17 and 19. The slow velocity of March 6 was probably the result of the small difference of density between the upper and lower layer. As there were no current measurements made on October 16, 1945, only the wave length could be calculated for that day.

Table 1--Internal waves off San Diego, California

Date	Period T	Wave length λ	Speed c	Average height H	Direction	Sea swell[a]	Depth	Position
	min	yards	knots	ft	° true		ft	° ′
PWT								
November 29, 1944 $15^h07^m - 15^h43^m$	12	105	0.27	16	201	1 - 1	300	32 36 N 117 28.5 W
March 6, 1945 $08^h20^m - 10^h40^m$	136	377	0.082	12	65	1 - 4	120	32 28.4 N 117 11.8 W
July 5, 1945 $15^h15^m - 16^h15^m$	16	360	0.68	15	111	0 - 1	120	32 34 N 117 12.3 W
July 5, 1945 $18^h15^m - 20^h00^m$	12	142	0.36	10	62	0 - 1	120	32 34 N 117 12.3 W
PST								
October 16, 1945 $21^h43^m - 22^h00^m$		203		6 (max.)	79	1 - 2	120	32 33 N 117 13 W
October 17, 1945 $12^h30^m - 14^h00^m$	44	126	0.084	5	77	1 - 2	120	32 33 N 117 13 W
October 18, 1945 $03^h28^m - 05^h30^m$	9	107	0.36	20 (max.)	253	1 - 2	120	32 33 N 117 13 W
October 19, 1945 $07^h37^m - 07^h55^m$	99	242	0.072	15	192	1 - 2	120	32 33 N 117 13 W

[a] Instructions to Marine Meteorological Observers, United States Department of Commerce, Circular M, June 1941, gives scale of sea and swell.

Table 2--Data on internal waves off San Diego, California

Number	Date	Speed	Time (PWT)
		knots	h m h m
1	November 29, 1944	0.27	15 10 - 15 40
2	March 6, 1945	0.082	08 30 - 10 30
3	July 5, 1945	0.68	15 15 - 16 15
4	July 5, 1945	0.36	18 15 - 20 00
5	October 17, 1945	0.084	13 33 - 15 00
6	October 18, 1945	0.36	04 28 - 05 30
7	October 19, 1945	0.072	08 37 - 08 55

Finally, to summarize what has been found thus far, the velocity vectors of the internal waves of Table 1 have been tabulated in Table 2 and plotted on Figure 10. Four of the waves are seen to be travelling toward shore. Number 6 may actually be reversed in direction by errors in the current measurement as previously indicated. The velocity of all the waves is less than one knot.

As presented here the internal waves have been considered to be of the sinusoidal progressive type, extending indefinitely perpendicular to their direction of propagation. This is only a first ap-

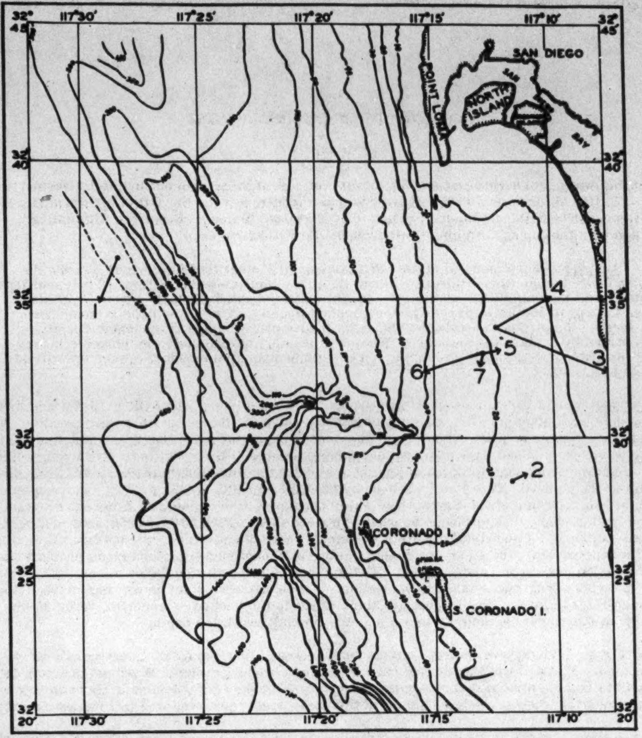

32° 45'
117°30'
117°25'
117°20'
117°15'
117°10'
32° 45'
SAN DIEGO
POINT LOMA
NORTH ISLAND
SAN DIEGO BAY
32° 40'
32° 40'
1
4
32° 35'
32° 35'
5
3
6
7
32° 30'
32° 30'
2
CORONADO I.
S. CORONADO I.
32° 25'
32° 25'
32° 20'
117°30'
117°25'
117°20'
117°15'
117°10'
32° 20'

Fig. 10--Map showing velocities of internal waves off San Diego, California

proximation as is evident from the irregularity of the records of Figure 8. Further work should attempt a more extensive correlation of the temperature in three dimensions as a function of the time.

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THE THEORY OF INTERNAL WAVES

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Abstract--The theory of motion of a horizontally stratified fluid under gravity is extended to include three linear gradients from the surface to the bottom. The resulting equation is then simplified to give the special cases in which first the upper layer and then the upper and lower layers are of constant density. The latter case is then shown by further simplification to lead to Stokes's theory of two layers of constant density separated by a sharp discontinuity. The wave lengths, as calculated by Stokes's theory and its extension to linear gradients, agree with previously measured values as well as is t[illegible]e expected.

Introduction--In two papers [see "References" at end of paper, UFFORD, 1947 a and b] strong evidence has been given for the existence of internal waves in the ocean of the progressive type with periods as short as a few minutes. In the second paper the wave length, period, and velocity of these waves were found from temperature measurements at three stations. If the experimental period is known, it is possible to calculate theoretically the wave length of the waves from the distribution of the density. This was first done by STOKES [LAMB, 1932, p. 372], who neglected friction and the rotation of the Earth. The water consisted of two layers of different constant densities with a sharp discontinuous boundary between them. FJELSTAD [1933] extended Stokes's theory to include a continuous distribution of density from the surface to the bottom. However, in this most general case, the equations must be integrated numerically, a laborious process that may be avoided in certain special cases. Fjelstad considered two simplified cases: (1) A linear change of density from the surface to the bottom or a change with some power higher than the first; and (2) three layers, in the first and third of which the density is constant, while in the second or middle layer the density increases exponentially with the depth.

Any change in density with depth may be approximated by a series of linear gradients of different slopes. Fjelstad has treated the case of a single linear gradient. A series of linear gradients leads to complicated boundary conditions; but, if the theory be extended to three layers with different linear gradients, a large number of the cases met in practice will be covered roughly.

Three special cases of the theory of three linear gradients are of interest. In the first the surface layer has a constant density corresponding approximately to isothermal water overlying a thermocline. Secondly, the bottom layer also may have a constant density corresponding approximately to isothermal water above and below a thermocline. Finally, if in the second case with constant density above and below a thermocline the thickness of the middle layer is allowed to approach zero, a third case will be obtained that is identical with Stokes's theory of a discontinuity between two layers of constant density.

Three linear gradients--The fundamental equation [FJELSTAD, 1933] for the motion of horizontally stratified water is

$$d[\rho_0(dw/dz)]/dz - (k^2/\sigma^2)[g(d\rho_0/dz) + \sigma^2\rho_0]w = 0 \qquad (1)$$

where z is the depth measured vertically up from the bottom, w is the vertical velocity amplitude of the water particles, ρ_0 is the density in the undisturbed state, and g is the acceleration of gravity.

$$\sigma = 2\pi/T \qquad (2)$$

in which T is the period

$$k = 2\pi/\lambda \qquad (3)$$

in which λ is the wave length. The speed of propagation of the waves is thus σ/k. With the special case to which the theory is being applied in mind, the ocean is divided into three layers numbered from the bottom up and of thickness h_1, h_2, and h_3. Let $h_1 + h_2 = h'$ and $h_1 + h_2 + h_3 = h$, the depth of the ocean.

Now let half the constant relative gradient of density be represented by

$$\beta = -(1/2\rho_0)(d\rho_0/dz) \tag{4}$$

The minus sign is inserted to make the constant β positive, for, since the density decreases as z increases from the bottom up, $d\rho_0/dz$ is negative. With this value of β, (1) becomes

$$(d^2w/dz^2) - 2\beta(dw/dz) + (k^2/\sigma^2)(2g\beta - \sigma^2)w = 0 \tag{5}$$

The solution of this equation is

$$w = e^{\beta z}(A \sin \gamma z + B \cos \gamma z) \tag{6}$$

where

$$\gamma^2 = k^2(2f\beta - 1) - \beta^2 \tag{7}$$

and

$$f = g/\sigma^2 \tag{8}$$

Now, since at the bottom of the ocean the particles have no vertical velocity, the boundary condition at the bottom of the lowest layer is

$$w = 0 \text{ for } z = 0 \tag{9}$$

which gives $B = 0$ in (6) and

$$w_1 = A_1 e^{\beta_1 z} \sin \gamma_1 z \tag{10}$$

in which the subscript 1 refers to the bottom layer. In the middle layer (6) gives

$$w_2 = e^{\beta_2(z - h_1)}[A_2 \sin \gamma_2 (z - h_1) + B_2 \cos \gamma_2 (z - h_1)] \tag{11}$$

since z will always be measured from the bottom of the ocean and the argument of the transcendental functions is measured from the bottom of the layer. Finally in the top layer (6) may be written

$$w_3 = e^{\beta_3(z - h')}[A_3 \sin \gamma_3 (z - h') + B_3 \cos \gamma_3 (z - h')] \tag{12}$$

Now at the boundary between the layers, the velocity and its spatial rate of change must be continuous

$$w_1 = w_2 \qquad dw_1/dz = dw_2/dz \tag{13}$$

$$w_2 = w_3 \qquad dw_2/dz = dw_3/dz \tag{14}$$

These boundary conditions, together with the boundary condition at the surface [FJELSTAD, 1933]

$$(dw/dz) - (k^2/\sigma^2)gw = 0 \tag{15}$$

permit the constants A and B to be eliminated and give an equation from which the wave length of the waves may be determined. The final result after some obscure manipulation is

$$\alpha_1\alpha_2 + \delta(\alpha_1 + \alpha_2) = \gamma_2{}^2 + \beta_2{}'(2\delta + \beta_2{}') \tag{16}$$

where

$$\alpha_i = (\gamma_i/\tan \gamma_i h_i) + \beta_i - \beta_3 \qquad i = 1, 2 \tag{17}$$

$$\delta = \gamma_3 \tan (\varphi - \gamma_3 h_3) \tag{18}$$

$$\tan \varphi = (\beta_3 - k^2 f)/\gamma_3 \tag{19}$$

$$\beta_2{}' = \beta_2 - \beta_3 \tag{20}$$

and to recapitulate

$$\sigma = 2\pi/T \tag{2}$$

$$k = 2\pi/\lambda \tag{3}$$

$$\beta = -(1/2\rho_0)(d\rho_0/dz) \quad \ldots\ldots (4)$$

$$\gamma_i^2 = k^2(2f\beta_i - 1) - \beta_i^2 \qquad i = 1, 2, 3 \quad \ldots\ldots (7)$$

and

$$f = g/\sigma^2 \quad \ldots\ldots (8)$$

in which λ = wave length of the internal waves, ρ_0 = density of the sea water in the undisturbed state, z = distance above the bottom of the ocean, g = acceleration of gravity, T = period of the internal waves, and h_i = thickness of the ith layer numbered from the bottom up. Similarly, the subscript i in α_i and γ_i refers to the ith layer with layer 1 at the bottom of the ocean, layer 2 in the middle, and layer 3 on the surface. λ, g, and z must have the same unit of length; the meter, for example, is a convenient one; and T and g must be expressed in the same unit of time, usually the second. It must be remembered that the period, T, is considered known from previous measurements.

When the observed constants are substituted in the equations, certain of the terms will be seen usually to be negligible, and therefore may be omitted. For example, the data of October 17, 1945 [UFFORD, 1947 b], lead to a large negative value for $\tan\varphi$. Thus $\varphi \doteq -\pi/2$, and

$$\delta \fallingdotseq \gamma_3 \cot \gamma_3 h_3 \quad \ldots\ldots (21)$$

for all except the smallest value of k.

In practical cases, (16) is approximately satisfied by $k_0 = (fh)^{-1/2}$, which corresponds to the ordinary surface wave when the wave length is long compared to the depth. f is given by (8), and h is the total depth of the water. Further solutions of (16) corresponding to short observed periods are found numerically. Finally the speed, c, of the waves may be found from the usual relation

$$c = \sigma/k \quad \ldots\ldots (22)$$

and will be expressed in m/sec if the wave length, λ, is measured in meters and the period, T, is measured in seconds as previously suggested.

Degenerate cases of three linear gradients--The first special case of three linear gradients is obtained by letting the density in the upper layer be constant, that is, $\beta_3 = 0$, which corresponds approximately to isothermal water overlying a thermocline. Then (16) reduces to

$$\alpha_1\alpha_2 + \delta_0(\alpha_1 + \alpha_2) = \gamma_2^2 + \beta_2(2\delta_0 + \beta_2) \quad \ldots\ldots (23)$$

where

$$\delta_0 = k \coth (kh_3 - \varphi_0) \quad \ldots\ldots (24)$$

$$\tanh \varphi_0 = 1/kf \quad \ldots\ldots (25)$$

and the different quantities have the same definitions and units as before, except that now β_3 must always be set equal to zero.

The second special case of three linear gradients is obtained by letting $\beta_1 = \beta_3 = 0$ in (16), that is, the bottom layer as well as the surface layer has a constant density corresponding approximately to isothermal water above and below a thermocline. Equation (23) may be used for this case with

$$\alpha_1 = k \coth kh_1 \quad \ldots\ldots (26)$$

which follows from (7) and (17) when $\beta_1 = \beta_3 = 0$.

The third and final reduction of the theory of three linear gradients, to the case of two layers of constant density separated by a discontinuity in density as treated by STOKES [in LAMB, 1932], may be made by setting $h_1 = h$, the thickness of the layer below the discontinuity; $h_3 = h'$, the thickness of the layer above the discontinuity; and by letting $h_2 \to 0$ and $\beta_2 \to \infty$ in such a way that

$$\beta_2 h_2 = (\rho - \rho')/(\rho + \rho') \quad \ldots\ldots (27)$$

in the limit. Equation (27) follows from (4) when the instantaneous gradient of (4) is replaced by the average linear gradient in the middle layer. Thus all the special cases of constant density and linear gradients treated up to the present have been shown to be included in (16).

Discussion and results--The wave lengths as found by measurements at three stations [UFFORD, 1947 b], are compared in Table 1 with the theoretical values. In order to calculate the wave length theoretically the period must be known. Unfortunately the value of the period calculated from three stations depends on the current under the ship. As there is still some uncertainty in the current measurement, the theory is under an initial disadvantage.

Table 1--Internal waves--measured and theoretical values of the wave length

Date and time (PWT)	Period measured	Wave length		Linear gradients
		Measured	Stokes	
	min	yard	yard	
November 29, 1944 15^h07^m - 15^h43^m	12	105	265	254
March 6, 1945 08^h20^m - 10^h40^m	136	377	375	-
July 5, 1945 15^h15^m - 16^h15^m	16	360	340	295
July 5, 1945 18^h15^m - 20^h00^m	12	142	235	186
October 17, 1945 13^h30^m - 15^h00^m	44	126	886	116 (Fifth order)
October 18, 1945 04^h28^m - 06^h30^m	9	107	152	129
October 19, 1945 08^h37^m - 08^h55^m	99	242	1721	238 (Fifth order)

Some of the lack of agreement in the wave lengths on November 29, 1944, probably also comes from the difficulty in measuring the difference in phase at the three stations as well as from errors in measuring the current. The second special case of the theory was used with one linear gradient between two layers of constant density which fitted the actual conditions reasonably well. Equation (16) together with the two degenerate cases with linear gradients leads to an infinite series of internal waves of a given period with decreasing wave length. The zero order wave, as has been pointed out previously, corresponds to surface waves; and it is the first order internal wave that is given in Table 1 except as otherwise noted therein. The excellent agreement shown in Table 1 for the wave length on March 6, 1946, is largely fortuitous, since, owing to the small temperature gradient, the difference in density above and below the thermocline was the difference of approximately equal small quantities, and hence subject to large error. The salinity was measured at four depths, including the surface, with Nansen bottles, and the average density of the upper and lower layers estimated from those four points. Thus the value of the wave length given by the dynamical equations is uncertain. As the thermocline was so narrow in depth, it was sufficiently close to a discontinuity to make it unnecessary to go to the approximation of a linear gradient.

The agreement between the measured and calculated wave lengths for July 5, 1945, is reasonably close. The 15^h15^m - 16^h15^m waves show the one case where the more accurate theory of linear gradients agrees less well with the measured wave length than the more approximate theory of Stokes.

For October 17 and 19, 1945, Stokes's theory does not agree with the observed wave length, and it is the wave length of the fifth order internal wave as calculated from the three linear gradients that agrees best with the observed value. Here the component of the current in the direction of propagation of the waves was closely equal to the speed of the waves, which made it difficult to get an accurate value of the period and lead to the long periods shown in Table 1. It is probable that Stokes's theory would have been more in accord with the measured wave length had it been possible to measure the period of the waves more accurately.

The equations involving linear gradients are sensitive to small variations in the period and the depth and density of the water, and probably require more accurate data for comparison than that available at present. However, it is of interest to see how fast the complexity of the wave pattern increases as further refinements are introduced. Figure 1 shows a plot of the two sides of (23) for

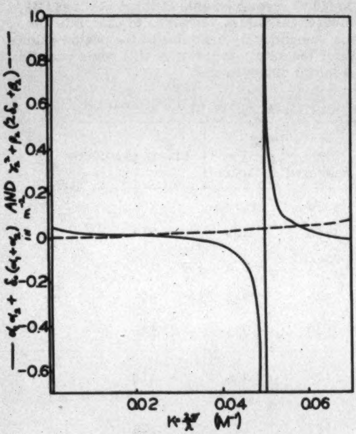

Fig. 1--Two linear gradients, July 5, 1945, 15^h15^m - 16^h15^m, from (23)

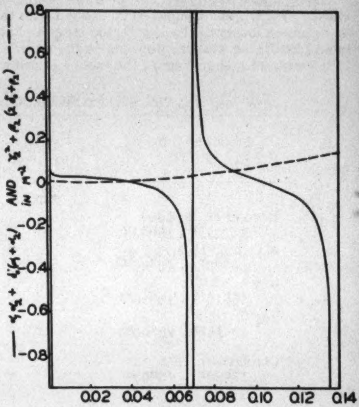

Fig. 2--Two linear gradients, July 5, 1945, 18^h15^m - 20^h00^m, from (23)

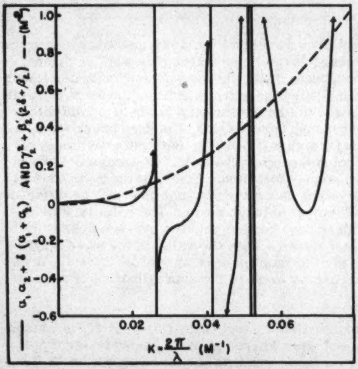

Fig. 3--Three linear gradients, October 17, 1945, 04^h28^m-06^h30^m, from (16)

the data of July 5, 1945, 15^h15^m - 16^h15^m. It can be seen that for small values of k, that is, large wave lengths, the curves representing the two sides of the equation run almost parallel and then suddenly cross, giving a value of k and hence of the wave length. A small change in the measured constants produces a relatively large change in the position of this crossing. The zero order root, $k_0 = 3.4 \times 10^{-4}m^{-1}$, corresponds to the ordinary surface wave when the wave length is long compared to the depth. The first order root, $k_1 = 0.0233m^{-1}$, was taken as that corresponding to the measured value of the wave length of the internal waves.

Now with approximately the same values of the density and the depth, but with a period of 12 instead of 16 minutes to correspond to the data of 18^h15^m - 20^h00^m, Figure 2 was obtained with the value of $k_1 = 0.036m^{-1}$. Here again a slight raising or lowering of the curve would change k radically. In both Figures 1 and 2, isothermal water overlay a sharp thermocline with a small gradient at depth. On October 17, however, the gradient in the layer above was greater than that below the thermocline, and the theory of three linear gradients was used. The three gradients together with the longer period, complicated the wave pattern as is seen from Figure 3, where several values of the wave length fall near the measured value. In this case the internal wave would theoretically be the sum of a series of waves of the same period with different phases and amplitudes; the height and apparent wave length of which would depend on the heights, wave lengths, and phases of the series of waves with the wave lengths taken from Figure 3. The wave length would thus vary from point to point along the wave. For simplicity, the value of the wave length given in Table 1 as calculated from three linear gradients is that nearest to the measured one.

Finally, the wave lengths of the waves on October 18, 1945, show as good agreement as is to be expected between the measured and theoretical values. Even if all the errors of measurement could be eliminated, the agreement would not be expected to be much improved, as the internal waves in the ocean are not simple sinusoidal waves, but produce variations of the properties of the ocean at a given point that form a time series which has here been represented by progressive sinusoidal waves as a first approximation.

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HIGH-TEMPERATURE PLAGIOCLASE IN THE OSLO IGNEOUS ROCKS

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It has been known for a long time that in potash feldspar the optical properties are functions of both the chemical composition and the thermal history of the feldspar. As a first approximation we may speak of low-temperature optics in adularia and common orthoclase characterized by a large axial angle, and high-temperature optics in sanidine characterized by a small axial angle. By heating orthoclase it is usually feasible to convert it into **sanidine**, optically. On cooling the **sanidine** type is preserved; indeed, no conversion of **sanidine** into the low-temperature type has been reported. One may conclude, therefore, that once the high-temperature type has been formed, its reversal to the low-temperature type is very slow; observations on natural feldspars indicate that **sanidines** are (meta) stable at ordinary temperatures for geological time periods.

In view of these facts, it is rather surprising that the optical properties of the plagioclases for so long have been regarded as independent of the thermal history of the minerals. As far as we know, nobody expected heat to cause permanent changes in the optical properties of plagioclases until BARTH [see "References" at end of paper, BARTH, 1931] 15 years ago, kept preparations of plagioclase at high temperatures for about 100 hours, thus demonstrating their actual conversion into high-temperature types. These preparations were afterward stored in order to see whether they eventually might reverse into low-temperature types. But no such change in the optical properties has as yet occurred; they still exhibit the **sanidine** high-temperature optics as when they were taken out of the furnace 15 years ago.

The results of these heating experiments would seem to indicate that plagioclase as well as potash feldspar possessed a high-temperature form, as well as a low-temperature form; and consequently that the chemical composition of plagioclase is not the only factor determining its optical properties.

Geologists have been slow to accept this implication. But during the War, an Austrian mineralogist [SCHOLLER, 1942], demonstrated the existence of a whole series of high-temperature plagioclases by exposing them to heat. These experiments were initiated by KÖHLER [1942 a and b], who had noticed that most of the natural plagioclases which show abnormal optical properties were derived from volcanic rocks; indeed, all plagioclases from such rocks are optically "abnormal," that is, they do not fit the migration curves. (Various curves for determining the chemical composition of a plagioclase from its optical constants have long existed. The most complete ones are probably the so-called migration curves given in stereographic projection by Duparc and Reinhard and also used by Winchell in his Optical Mineralogy, and by others. A plagioclase whose optical constants do not fit the migration curves is called "abnormal.") He concluded, therefore, that the volcanic plagioclases possess "**Hochtemperaturoptik**," while plagioclases from deep-seated and metamorphic rocks possess "Tieftemperaturoptik." And the migration curves of Duparc and Reinhard correspond to the low-temperature plagioclases. These results have been corroborated by TERTSCH [1942].

In view of these facts it is interesting to note that OFTEDAHL [1944] has observed high-temperature plagioclases in the Permian igneous-rock province of Oslo, Norway. The Oslo Province, as is generally known, consists of a mildly alkaline rock suite containing plutonic (subvolcanic), intrusive, and effusive members. All effusives in the province carry high-temperature plagioclases: Basalts, trachybasalts, trachy-andesite, and trachytes. (Rocks of trachytic affinities are developed as rectangle porphyries or as rhomb porphyries.)

In intrusive rocks, high-temperature plagioclase has been observed in dikes of rhomb porphyry and in akerites of intrusive character. Akerite is a syenodiorite which is not typical either of a deep-seated rock or of an extrusive; it is normal eugranitic, rather fine-grained, with a rectangular development of the feldspars whose bounding faces are 001 and 010. The name should not be applied to normal syenodiorites but only to such rocks which show the characteristic texture.

In plutonic rocks high-temperature plagioclases have been observed in certain larvikites. The larvikite is a coarse-grained syenite with a small amount of plagioclase [BARTH, 1944]. About one-third of the Oslo sub-volcanic massif is made up of larvikite. Certain types exhibit pseudoporphyric structure; the elongated rhomb-shaped crystals of feldspar attaining several centimeters are then fluidally arranged in a feldspathic mesostasis consisting of crystals the dimensions of which are two-thirds mm.

It is worthy of notice that an apparently deep-seated rock has this kind of feldspar. It supports the idea of a shallow level of congealing previously suggested by the study of, for example, certain textural peculiarities.

BRÖGGER [1890] thought that many of the Oslo plutonites had crystallized only a few hundred feet below the surface. HANS CLOOS [1936] has characterized the plutonites of fault zones generally as sub-volcanic bodies of particularly great size.

The optical orientation of the high-temperature plagioclase series is given quantitatively in the tables published by Köhler and his co-workers. Köhler recognizes two distinct series; high-temperature plagioclase and low-temperature plagioclase. He has drawn curves corresponding to the two series. However, our measurements with the universal stage indicate that no such two distinct series are present; the usual low-temperature series is connected with the Köhler high-temperature series by intermediate values.

A great many individual crystals have been measured and plotted on stereographic diagrams by us. Among them we have chosen those that we think are the most reliable. They include 11 sets of complete measurements on Carlsbad twins in the stereographic diagrams of which the triangle of error appearing by the graphic determination of the twin axis has reduced itself to a point, that is, the diagrams are theoretically of high accuracy.

In two of the feldspars the projection points of α, β, and γ fall exactly on the Köhler high-temperature curves, but the corresponding projection points of the nine other feldspars do not fit either set of curves; they are systematically displaced from the theoretical positions on the low-temperature curves towards the corresponding positions on the high-temperature curves. Thus each crystal possesses its individual optical orientation, and consequently, its individual history of cooling. The temperature of crystallization is not the only governing factor; also the rate of cooling must be considered. Quick cooling will freeze and preserve the high-temperature type, slower cooling will permit an approach to the low-temperature type.

A feldspar of high-temperature optics must have crystallized at high temperatures, but a feldspar of low-temperature optics may also have crystallized at high temperature if cooling has been slow enough.

A few words about the mechanism of the low-high changes may be appropriate. Our knowledge of the polymorphic phenomena and the mechanism of the solid state makes it probable that the permanent changes in the optical orientation of feldspars thus induced by heat are due to intermolecular diffusion of Al and Si in the crystalline lattice in the manner suggested in a previous paper by one of us [BARTH, 1934]. Subsequently an analogous mechanism has been demonstrated to occur in lithium ferrite by BARBLAU, BRANDENBERGER, and NIGGLI [1943]. In this substance, when exposed to temperature above ca 600°C, a slow interdiffusion of Li and Fe takes place: $Li_2Fe_2O_4 <$ 570° is tetragonal, and both Li and Fe have fixed positions in the lattice. But when heated for several days at 670° the ions of Li and Fe interdiffuse and become statistically distributed over the several lattice positions (equi points). The structure becomes cubic of the NaCl type, and can be written $(Li, Fe)_4O_4$.

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EFFECT OF REMOVAL OF STREAM-BANK VEGETATION UPON WATER YIELD

Earl G. Dunford and P. W. Fletcher

Abstract--This is a preliminary report of results of a study wherein vegetation has been cut along the stream bank of a 22-acre watershed on the Coweeta Experimental Forest. Previous measurements on this forest have shown that complete removal of vegetation results in notable gains in water yield because of a reduction in transpiration. The cutting of riparian growth has also resulted in an increase in yield of sufficient magnitude to be significant in water-resource management.

Preliminary examination of the data immediately following cutting shows a virtual elimination of the diurnal fluctuation during the growing season. This indicates that the vegetation immediately adjacent to the stream is making appreciable demands upon groundwater supplies contributing directly to streamflow.

It can be concluded, therefore, that important gains in water yield during the growing season in the southern Appalachian region may be realized with relatively little effort by eliminating the transpiration draft of riparian vegetation. This procedure can be of much practical value during drought years for municipal and industrial watersheds, when even small increases in yield are of unusual importance.

Diurnal variations in runoff have long been associated with the combined draft of evaporation and transpiration upon water in streams and the adjacent groundwater aquifer. This evapotranspiration factor has been termed "consumptive use" by BLANEY, TAYLOR, and YOUNG [see "References" at end of paper, 1930]. Except for water losses through deep seepage, it is almost entirely responsible for the difference between precipitation and runoff within the water year.

The importance of water losses through transpiration and evaporation has been emphasized repeatedly by investigators, particularly in semi-arid regions [BLANEY, TAYLOR, and YOUNG, 1930; BLANEY, TAYLOR, YOUNG, and NICKLE, 1933; TROXELL, 1936; WHITE, 1932; WICHT, 1941; and YOUNG and BLANEY, 1942]. In the southern Appalachian region water resources have been drawn upon heavily to meet the constantly increasing demands of industries and municipalities. In numerous instances supplies have become critically low. This situation has led to an active interest on the part of industrial and municipal watershed managers in the possibilities for augmenting existing supplies during summer drought periods.

On the Coweeta Experimental Forest, studies have already demonstrated that cutting vegetation over the entire surface of an experimental watershed will increase water yield as much as 17 area inches a year [HOOVER, 1944]. This increase, it was concluded, was derived almost entirely from the complete elimination of transpiration. The net effect of evaporation was unchanged because increased soil evaporation was offset by decreased interception. This study [HOOVER, 1944] has afforded an estimate of the maximum effect achieved by reducing transpiration in a superhumid climate.

Following this line of investigation, it was assumed that vegetation having continuous access to the water table is responsible for losses relatively greater in proportion than the area it occupies. Use of water in such locations continues at a high rate throughout the growing season and reaches a maximum during rainless periods when transpiration by plants in drier areas is limited by lowered groundwater tables. Therefore, it was concluded that an important measure of the transpiration draft by vegetation growing in zones of high water tables can be gained by studying the effect of its removal on streamflow in a small experimental watershed.

Transpiration and evaporation of water by stream-bank vegetation have been estimated with some success in the past by measuring the flow of water entering and leaving a given section of stream channel [TROXELL, 1936, and YOUNG and BLANEY, 1942]. It has been pointed out that determinations made in this manner may be subject to non-measurable movements of inflow and outflow. Studies of this nature have been conducted in Temescal Creek, Coldwater Canyon, and the Santa Ana River in Southern California. Daily losses in flow attributed to transpiration and evaporation in Coldwater Canyon varied in amounts from 0.12 to 0.50 acre inches per 1000 feet of canyon bottom. In Temescal Creek losses per day from 12.8 acres increased gradually from 0.02 to 0.64 acre inches from April 16 to May 27, 1929.

The present paper describes the methods of arriving at evapotranspirational losses by a comparison of streamflow before and after cutting of the stream-bank vegetation. It is believed that such a comparison will yield more direct information than the methods employed heretofore. One advantage of the direct treatment method is the fact that non-measurable inflow and outflow seepage do not affect the relative differences in flow due to treatment. On the basis of observations previously made at Coweeta Experimental Forest, it was concluded that measured effects of cutting stream-bank vegetation do not reflect any substantial change in evaporation rates [HOOVER, 1944].

Because of the limited scope of this investigation, the results obtained must be regarded as only indicative of the water volumes utilized by vegetation growing in zones of high water tables. Cutting was confined to a strip of vegetation adjacent to an active stream in a small watershed. No attempt was made to include other possible zones of high water tables existing within the area. This preliminary test will be followed by a more comprehensive study which will include the measure of cutting effects upon water temperatures and aquatic biology.

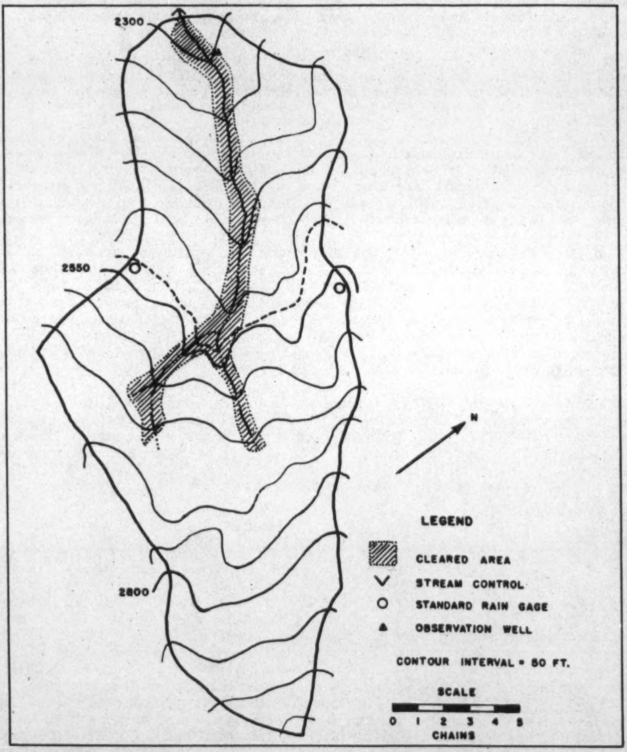

Fig. 1--Topographic map of Area Number 6, Coweeta Experimental Forest, showing area cleared of stream-bank vegetation

The experiment is being conducted on the Coweeta Experimental Forest in the Appalachian Mountains of western North Carolina. The region is one of high rainfall, averaging about 70 inches a year, distributed rather uniformly throughout the year. The growing season extends from April 15 to October 15, with a mean temperature of 65° F. Natural vegetation is abundant and primarily deciduous. For the purposes of investigation a 22-acre watershed designated as Area Number 6 was selected (see Fig. 1). The aspect is northwest and elevations range from 2282 to 2955 feet. Continuous records of streamflow from a sharp crested V-notch weir have been obtained since July 1934.

A treatment area was delineated by assuming that all vegetation at a ground level within 15 feet in elevation above the stream channel had access to the continuous water table. Within those limits was an area of 2.62 acres or 12 per cent of the total watershed area. The length is 1600 feet and the width varies from 60 to 250 feet. During the period of July 21 to 25, 1941, all woody vegetation within this zone was cut, lopped, and scattered (see Fig. 2). The soil surface was disturbed as little as possible and all debris due to cutting was removed from the channel.

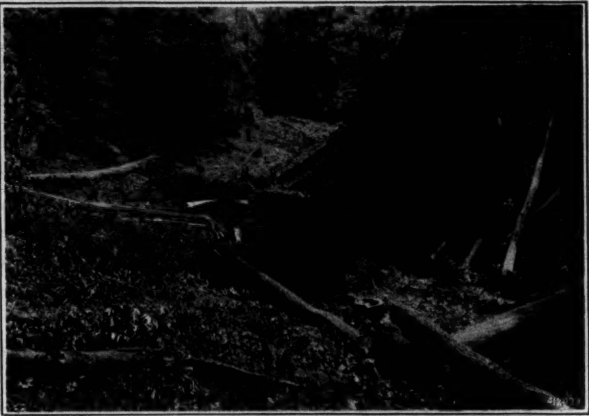

Fig. 2--View of Area Number 6 after cutting stream-bank vegetation [photo by U. S. Forest Service]

A complete tally of the vegetation on the cutting area showed a total of 3563 stems larger than 0.5 inch in diameter. The greater portion of this number was represented by an understory of rhododendron, mountain laurel, azalea, witch hazel, black birch, and associated species. The principal tree species in the overstory were chestnut oak, yellow poplar, red maple, and hickory. Sprout growth was quite rapid during the 1942 growing season, one year following treatment. Species such as yellow poplar, red maple, and hickory made an early appearance and grew vigorously. Rhododendron still remains the most abundant species. No further cutting was done following the original treatment.

In the analysis of the effects of cutting, two approaches have been considered. The first of these is based on a comparison of data obtained from the treated watershed alone. The second, introduced as supplementary evidence, employs data from an adjoining watershed serving as an untreated check. Treatment effects derived from either method are subject to variables which cannot be controlled other than by statistical procedures. In view of the preliminary nature of the present study, the possibilities of increasing the accuracy of the estimates by use of statistics were not explored.

A fairly reliable expression of streamflow during rainless periods following cutting can be depicted by a smoothed groundwater depletion curve. Such a curve was developed from data obtained during August and September of 1941, and June to September 1942. A close approximation of the average daily flow is maintained throughout, since it is based on a series of instantaneous midnight readings from the hydrographs. The curve has been synthesized from a group of individual segments of post-treatment hydrographs adjusted horizontally to positions providing the best fit of midnight points. Average readings on a vertical scale at each of these reference points were then obtained, from which the smoothed curve was drawn.

Having an expression of post-treatment stream behavior depicted by the synthesized depletion curve, a measure of treatment effect may then be estimated. In Figure 3 is shown a curve, B, representing the observed flow for a ten-day period just prior to treatment. This period represents the groundwater depletion following a storm producing a peak flow of 7.023 csm. The diurnal fluctuations shown are characteristic of the flow of Area Number 6 prior to treatment. If it can be imagined that the ten-day period shown in Figure 3 occurs immediately following the cutting of stream-bank vegetation, one can assume that the flow from Area Number 6 will be represented by a portion of the synthesized depletion curve, A. After inspection of the hydrograph of the storm preceding curve B, it was estimated that the initial point on the groundwater depletion curve was at a discharge of 1.0225 csm occurring at 08^h00^m, June 12, 1942. This can be assumed to represent a point of time immediately following treatment. Post-treatment stream-flow behavior will then follow the pattern shown by a portion of the synthesized depletion curve, A, beginning at a discharge rate of 1.0225 csm.

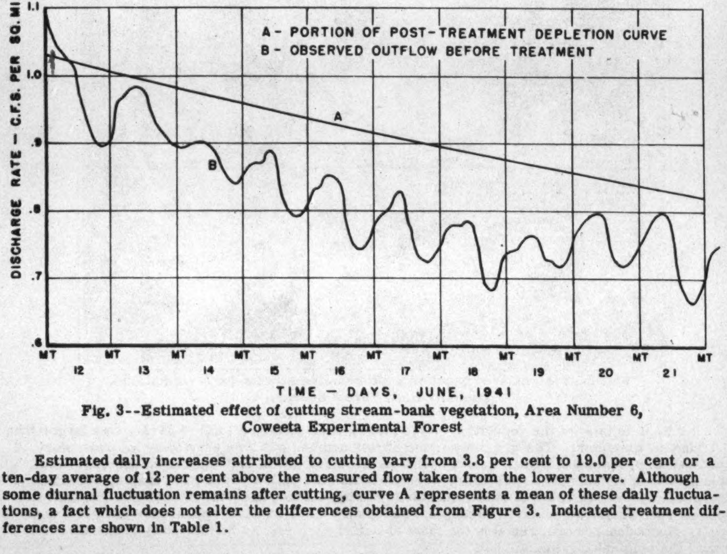

Fig. 3--Estimated effect of cutting stream-bank vegetation, Area Number 6, Coweeta Experimental Forest

Estimated daily increases attributed to cutting vary from 3.8 per cent to 19.0 per cent or a ten-day average of 12 per cent above the measured flow taken from the lower curve. Although some diurnal fluctuation remains after cutting, curve A represents a mean of these daily fluctuations, a fact which does not alter the differences obtained from Figure 3. Indicated treatment differences are shown in Table 1.

An interesting interpretation may be derived from the characteristics of the post-treatment depletion curve A. Its position with respect to pre-treatment depletion curve B in Figure 3 indicates that the transpiration losses are not represented by the daily fluctuations alone. This would tend to bear out some conclusions reached by TROXELL [1936] in his discussion of diurnal fluctuations in the Santa Ana River. He states that the practice of connecting the periods of maximum discharge of diurnal fluctuations and assuming that the difference between the curve thus obtained and the actual flow represents transpiration loss will give results which are too conservative. The interpretation gained from Figure 3 is that transpiration by stream-bank vegetation is not only responsible for a daily depression in the hydrograph but also for a progressive drain on the groundwater reservoir in excess of that which would normally occur if there were no transpiration.

A second approach to the problem of estimating the effects of removal of stream-bank vegetation was investigated. This method involves the use of data from a check watershed to aid in the

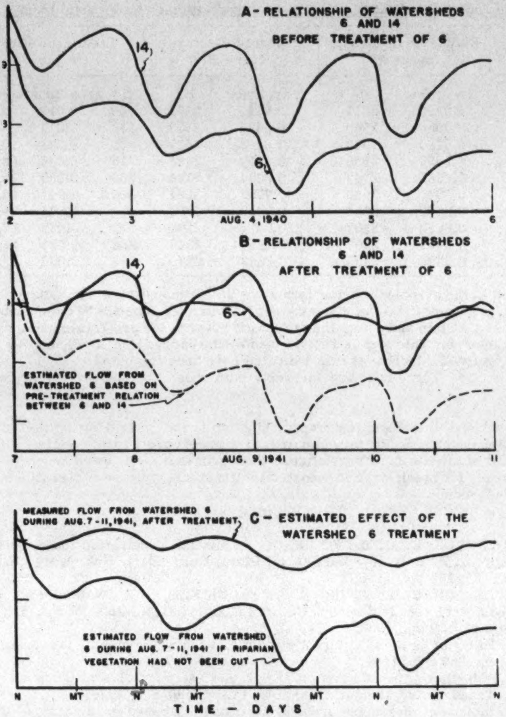

Fig. 4--Estimated increase in water yield due to cutting of stream-bank vegetation, Coweeta Experimental Forest

interpretation of results before and after treatment in Area Number 6. The advantages of this comparison lie in the fact that climatic factors affecting transpiration before and after treatment can be controlled statistically. The following discussion does not fully exploit the advantages of this method, but a more comprehensive investigation will be made of its possibilities in subsequent analyses planned for this study. The graphical representation in Figure 4, however, is indicative of the results which may be found.

The check watershed, Area Number 14, employed in this comparison, is 152 acres in area and lies adjacent to Area Number 6. The general aspect is north and the vegetation along the stream banks is similar to that existing in Area Number 6 prior to cutting. Preliminary investigation indicates that a well-defined relationship exists between the discharge rates of both watersheds. For the purposes of graphical demonstration, two four-day periods were selected, one before and one after treatment. Hourly discharge rates in csm were plotted as shown in Figures 4A and 4B. The discharge rate in Area Number 14 is substantially the same before and after treatment. For Area Number 6, however, treatment appears to have accomplished two things: (1) Raised the average level of discharge rates; and (2) eliminated much of the diurnal fluctuation in flow. The residual fluctuation indicates that there was not a complete removal of the vegetation affecting the groundwater supplies adjacent to the stream.

Table 1--Estimated effect of cutting stream-bank vegetation on water yield from Area Number 6

Day	Estimated discharge curve A		Measured discharge curve B		Treatment effect (A - B)		
	av. csm	ft^3	av. csm	ft^3	ft^3	area inches	pct
1	1.0190	3011	0.9820	2902	109	0.012	3.8
2	0.9950	2940	0.9482	2802	138	0.015	4.9
3	0.9720	2872	0.8822	2607	265	0.028	10.2
4	0.9495	2806	0.8419	2488	318	0.034	12.8
5	0.9280	2742	0.8034	2374	368	0.039	15.5
6	0.9070	2680	0.7753	2291	389	0.041	17.0
7	0.8870	2621	0.7452	2202	419	0.044	19.0
8	0.8670	2562	0.7411	2190	372	0.039	17.0
9	0.8485	2507	0.7597	2245	262	0.028	11.7
10	0.8300	2453	0.7343	2170	283	0.030	13.0

A third step in the graphical comparison gives an estimate of the increase in yields due to treatment. This is accomplished by matching the flow in Area Number 14 before and after treatment as closely as possible and noting the difference between the pre-treatment and post-treatment flows in Area Number 6. This step is represented by the dashed line in Figure 4B and the final comparison in Figure 4C. Increases thus indicated have been computed at 13, 17, and 19 per cent for a three-day period. These compare favorably with those obtained by the depletion-curve method.

It can be concluded, therefore, that important gains in water yield during the growing season in the southern Appalachian region may be realized with relatively little effort by eliminating the transpiration draft of stream-bank vegetation. This procedure can be of much practical value during drought years for municipal and industrial watersheds, when even small increases in yield are of unusual importance.

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SUITABILITY OF ICE FOR AIRCRAFT LANDINGS

Robert P. Sharp

Abstract--The thickness of ice required for aircraft landings on skis can be calculated from the following formulas:

$$S_r = (15/4)\sqrt{W_t};\quad S_\ell = (27/8)\sqrt{W_t};\quad S_s = (27/4)\sqrt{W_t}$$

S_r is the thickness in inches for river ice, S_ℓ for lake ice, and S_s for old sea ice. W_t is the weight of the plane in tons. These formulas allow for the static weight of the plane and its dynamic impact at the time of landing. The thicknesses calculated are for ice formed at or below 16°F. For ice formed at higher temperatures the thicknesses must be increased by about 25 per cent. S_s is for old sea ice. Young sea ice is weaker and must be about three times as thick as river ice. Planes on wheels require about 20 per cent greater thickness than calculated from the above formulas. Ice is stronger at lower temperatures, and its strength increases about four times between 23°F and - 76°F. Salt, air bubbles, included vegetation, cracks, and heavy snow cover all make ice weaker. Ice also experiences elastic fatigue under constant heavy use and must be rested frequently.

Freeze-up usually takes place many days or even several weeks after the mean air temperature falls below freezing. After the water temperature reaches freezing, the rate of formation and growth of ice may be predicted from a curve of degree days of frost or calculated by formula.

Salinity retards freezing by lowering both the freezing point and the maximum-density temperature. Currents, waves, and snow cover also retard the growth of ice, but under proper conditions wind can be an asset. Ice continues to increase in thickness well beyond the period of minimum air temperature. Thereafter, it maintains its maximum thickness for a short time before showing a rapid decrease just prior to break-up. Ice deteriorates considerably in spring, and its strength decreases more rapidly than its thickness. This is particularly true of lake ice which "candles." Salty ice honeycombs extensively.

The surface of most frozen fresh-water bodies is usually suitable for landings, but sea ice is often rough and broken. However, many successful landings and take-offs have been made from the ice pack, and a suitable place can frequently be found. Firm, wind-packed snow can have a bearing strength of 100 to 200 lb/in^2, but wind-swept surfaces are often rough owing to drifts and sastrugi.

Introduction--The following is strictly an office compilation from a variety of sources. It contains no original material and is not based on the experiments or field observations of the compiler, who is no cryologist. These data were assembled during World War II and issued as a preliminary report of the Arctic, Desert, and Tropic Branch of the Army Air Forces Center. The report has been cleared for publication by the United States War Department and is reproduced here in essentially its original form.

The major aim is to provide information pertinent to some aspects of aircraft operations on ice, particularly landings. The formation of ice, some of its physical characteristics, and other factors affecting its suitability for aircraft operations are considered briefly. These matters are not treated from a geographical standpoint, although an attempt is made to provide some means by which approximate thicknesses of ice in remote regions can be predicted.

Problems of ice in relation to aircraft landings have been most fully studied by the Russians. Digests of this Russian information and considerable data from other sources have been made available through the cooperation of A. D. Bajkov, formerly of the Air Technical Service Command, United States Army Air Forces. Much of this compilation should be credited to Bajkov.

Formation of ice--It is now generally concluded that H_2O molecules are at least temporarily bonded together in twos and threes [see "References" at end of paper, DORSEY, 1940]. The single molecule, H_2O or hydrol, is water vapor; the double molecule, $(H_2O)_2$ or dihydrol, is water in the liquid form; and the aggregate of three molecules, $(H_2O)_3$ or trihydrol, is ice. With increasing temperature dihydrol (water) tends to change to hydrol (water vapor) and with decreasing temperature to trihydrol (ice). The significant relation here is that dihydrol (water) contains trihydrol (ice) in solution. At 100°F water is said to contain 16 per cent ice in solution, and this rises to 37 per cent approaching the freezing point [BARNES, 1928], although these figures may not be universally accepted [DORSEY, 1940]. At the freezing point water becomes a saturated solution, and ice is precipitated. Super-cooled water behaves essentially like any supersaturated solution.

Dissolved salts lower the freezing point and produce a significant difference in the freezing temperature of fresh and sea water as shown in Table 1. Average sea water has a salinity of 35 parts per thousand and freezes at 28°.6 F [WORDIE and ROBERTS, 1944].

Table 1--Salinity and freezing points

Salinity	Freezing points	
parts/1000	°C	°F
0	0	32
5	- 0.3	31.5
10	- 0.5	31.1
15	- 0.8	30.6
20	- 1.1	30
24.695	- 1.332	29.61
25	- 1.35	29.57
30	- 1.6	29.12
35	- 1.9	28.58
40	- 2.2	28.0

Salinity also affects the freezing point through its influence on density [WORDIE and ROBERTS, 1944]. Fresh water reaches its maximum density at 39°.2 F, so density currents do not develop with further cooling, and only the surficial layer need be cooled to the freezing point before a layer of ice can form. Conduction complicates this simplified picture to some degree. Water with a salinity of 5°/00 has its greatest density at 37°.2 F, so the entire body of water must be cooled to that temperature before density currents cease. The maximum-density temperature and the freezing temperature approach each other as salinity increases. They coincide when the salinity is 24°.695/00. This means that with a salinity of 24°.695/00 or more density currents operate clear down to the freezing point, and the entire water body must be cooled to this temperature before a layer of ice can form on the surface. The rapidity of cooling and the total drop in temperature are often so great and density currents so slow that ice probably does form in nature before the temperature of the entire body is lowered to the freezing point. Regardless of this, it is clear that salinity retards freezing by lowering the maximum-density temperature as well as by lowering the freezing point.

Heat is lost from water chiefly by conduction, convection, radiation, and evaporation, and any factors affecting these processes are significant in the formation and growth of ice.

Zenith angle of the sun, and therefore latitude, are important because with a low sun water surfaces reflect a considerable part of the solar radiation. The following information and figures are from DEVIK [1944]. In northern latitudes in winter the heat received from direct solar radiation and from diffused radiation is far below the amount of heat lost from the water. Loss of heat by infrared radiation is nearly three times as great with a clear sky as with a complete cloud cover. Heat loss by convection is controlled by temperature difference between the water surface and air and is increased by wind. At 14°F air temperature, water temperature 32°F, and no wind, the heat loss by convection is 18.1 cal/in^2/hr. With a wind speed of 1.12 mph the heat loss increases to 74.2 cal/in^2/hr. Heat lost by evaporation depends largely upon vapor pressure gradient and wind. At air temperature 14°F, water temperature 32°F, a vapor pressure 2.6 mm mercury, and no wind, the loss by evaporation is 10.9 cal/in^2/hr. Under the same conditions but with a wind speed of 1.12 mph it is 49.7 cal/in^2/hr [DEVIK, 1944]. Although wind aids cooling by increasing heat loss through convection and evaporation, it retards freezing by disturbing the surface of the water. However, freezing during a calm following a windy period is benefited by the cooling produced by the wind. Once a layer of ice is formed, wind can aid its growth by blowing away the snow that falls on its surface or by packing the snow more firmly and thereby reducing its power of insulation.

At 14°F, vapor pressure of 2.6 mm mercury, zero wind velocity, no cloud cover, sun altitude 5°, and water temperature 32°F, the total heat lost exceeds the heat gained by 94.8 cal/in^2/hr. With all conditions the same except for a wind velocity of 1.12 mph and cloudiness ten, the heat lost exceeds the heat gained by 150 cal/in^2/hr. In the first case ice will be produced at 0.079 in/hr and in the second at 0.126 in/hr [DEVIK, 1944].

Snow falling into water has a cooling effect, but this is likely to be relatively insignificant except when the water is already close to freezing. However, at this temperature snowflakes aid freezing both by cooling and by providing nuclei around which ice crystals develop.

Water cools slowly and its surface temperature always lags behind the rise and fall of the mean air temperature. In the Murmansk-White Sea area, rivers usually freeze about three weeks after the mean air temperature falls below 32°F. This is probably representative for many similar regions. Lakes usually freeze a little earlier. Inland waters containing much vegetation do not freeze as quickly as clear water, and swift currents in rivers obviously retard freezing and may even prevent it.

The following factors facilitate the formation of ice in the sea: (1) Freshening of the water by precipitation, rivers, or melting of ice; (2) hindrance of wave and other water motion; (3) presence of floating chunks of old ice which cool the water and reduce wave motion; (4) shallow water; (5) lack of currents; and (6) lack of storms [SMITH, 1932, and TRANSEHE, 1928].

Freezing of sea water is first indicated by a greasy or oily appearance and shortly thereafter small spicules and plates called "frazil ice" become visible. Frazil ice increases until the water is covered with a mush of crystals called "slush" or "sludge." This material gradually agglomerates into roughly circular flat masses called "pancakes," and the pancakes are eventually cemented together to form "floes" and "sheets" [WORDIE and ROBERTS, 1944]. Ice formed on bodies of fresh water is usually relatively clear and smooth, but in the sea such ice forms only in protected coves and narrow lanes or leads cutting through the ice pack. In fast-running streams spongy accumulations of frazil ice on the bottom and along the shores are usually the first phase in the freeze-up [DEVIK, 1944].

Growth and thickness of ice--Heat loss at the rate of 120 cal/in^2/hr causes ice to form at the rate of 0.1 in/hr if the water temperature is 32°F [DEVIK, 1944]. Newly formed ice may grow to a thickness of four or five inches in the first 48 hours. Thereafter growth is slower. Once a solid layer of ice is formed, further growth depends chiefly upon conduction of heat through the ice to the colder air above, and this in turn depends upon the steepness of the temperature gradient. The effect of an increasing ice thickness and a snow cover upon heat loss is illustrated in the following diagram, Figure 1. Evaporation from the ice surface and radiation, which takes place only when the ice is clear and its surface free of snow, play a small part. Convection currents in the water usually retard the growth of ice. Sea ice seldom grows to a thickness greater than five to seven feet in the first year. If unbroken through the second winter, the thickness may reach seven to eight feet at the most. Ice in the far northern rivers and lakes can grow to a thickness of six to eight feet in a single season. With rare exceptions this fresh-water ice disappears entirely in summer, but sea ice is perennial in the Polar Basin. Perennial sea ice may grow in thickness during the summer by the following means. Snow on the surface melts, and the water runs down through cracks and holes to form a layer of fresh water under the ice. Since the temperature of the underlying salt water is usually lower than the freezing point of fresh water, a layer of fresh-water ice is formed on the bottom of the sea ice [WORDIE and ROBERTS, 1944].

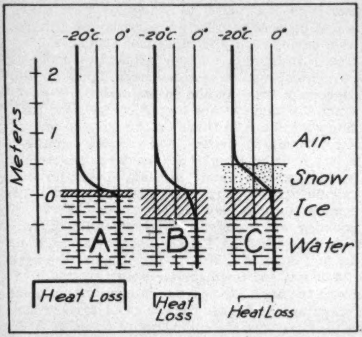

Fig. 1--Thermal gradient and heat loss through: A, thin ice; B, thick ice; C, thick ice and snow [after Devik]

Ice in the Polar Basin is seldom less than 3-1/2 to 4-1/2 feet thick, and Nansen [ZUBOV, 1940] reports a maximum thickness of 13 ft ten inches produced by about four years of normal growth. Much greater thicknesses can be formed by rafting, tidal overflow, other types of flooding, spray, and splashing. Ice in hummocks and pressure ridges sometimes attains a thickness of 50 to 100 feet.

The rate of growth of fresh-water ice may be calculated by Formula (1) [BARNES, 1928]:

$$t = (LSE/K\theta)(1 + E/2) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

in which t is the time in seconds for the ice sheet to attain a thickness E in centimeters; L is the heat of fusion, 80 cal/gm; S is the density of ice, 0.9166; K is the conductivity of ice, 0.0057 cal per degree difference of temperature C, per cm^2, per sec; and θ is the difference in temperature, C, between the underside of the ice sheet, assumed 0°C, and the air temperature.

Table 2 provides examples of the results obtained from (1) with the above assumptions. Thicknesses are converted from centimeters to inches and temperatures from Centigrade to Farenheit.

Table 2--Rate of growth of an ice layer

Thickness of ice	Temperatures			
	14°F	- 4°F	- 22°F	- 40°F
in	day	day	day	day
1	0.086	0.043	0.029	0.021
6	1.95	0.98	0.65	0.49
10	5.19	2.60	1.73	1.29
12	7.38	3.69	2.46	1.85
24	28.60	14.30	9.53	7.15
36	63.69	31.85	21.23	15.92

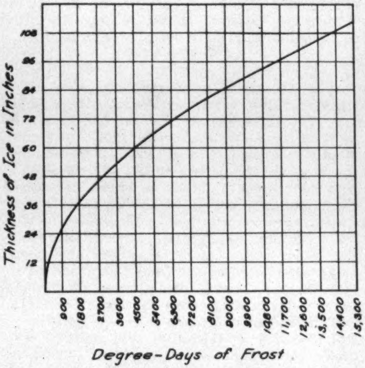

Fig. 2--Rate of growth of ice

The approximate thickness of ice may be predicted from the curve of Figure 2 if the temperatures at a specified locality are known. Even if exact temperatures are not available estimates can probably be made from a general knowledge of weather conditions in the region. In calculating the degree days of frost it must be remembered that 0°F is 32° of frost. Furthermore, it is better to add up the mean number of degrees of frost for each day or group of days having about the same mean degrees of frost than to make a single calculation using a large number of days and a mean figure for the degrees of frost for the entire period. Days on which the temperature was below freezing for only part of the 24 hours can be ignored unless exceptionally numerous, and excessive refinements in calculation of degree days of frost are neither necessary nor justified. Examples of calculations of degree days of frost follow. Assume a specified day had eight hours below freezing, and the mean temperature for those eight hours was 23°F. The degree days of frost for that day are $8/24 \times 9 = 3$. Suppose the next day had temperatures below freezing for the entire 24 hours, and the mean temperature was 20°F. The degree days of frost for this day are 12. If the next ten days had approximately uniform mean temperature, say - 20°F, and all hours were below freezing, the degree days of frost for the ten days are 520. The total degree days of frost for the 12-day period described above would be 535. A glance at Figure 2 shows that the curve permits considerable approximation in calculating degree days of frost without seriously affecting the final results. Obviously other factors such as wind, snow, and currents introduce complications difficult to evaluate and not allowed for in the graph. The lowermost end of the curve is none too reliable because freezing weather may exist for a number of days before ice starts to form. Once a layer of ice has begun to form, the curve is much more reliable unless thawing occurs.

Weekly measurements of ice thickness in far northern harbors [BERNIER, 1910, and LOW, 1906] give curves which rise steadily for two-thirds to three-fourths of the total period, flatten off briefly, and then drop abruptly just prior to breakup.

Physical nature and structures of ice--Ice is reported to precipitate as a colloid from water super-cooled by as little as a few thousandths of a degree [BARNES, 1928]. The colloidal particles agglomerate and form plate- and spicule-shaped crystals [BARNES, 1928]. In calm fresh water, ice forms long hexagonal prismatic crystals arranged perpendicular to the water surface. If undisturbed these crystals grow into long pencils equal to the thickness of the ice layer. Freshened sea ice may also develop this structure, but young sea ice is said to consist of an uppermost one-half-inch layer of thin horizontal ice plates about the size of a fingernail with the ice beneath consisting of vertical prismatic crystals [WORDIE and ROBERTS, 1944]. Some young fresh-water ice has a similar arrangement. Ice crystals have gliding planes parallel to the base, but experiments show that aggregates of parallel prismatic crystals may yield more readily along the prismatic face than along the base [MATSUYAMA, 1920].

New sea ice usually contains five to 15°/00 salt. Ice formed slowly or in calm weather has less salt than ice formed rapidly or in rough weather. For example, young sea ice formed at 14°F has four to 6°/00 salt, but that formed at - 40°F has ten to 15°/00 [WORDIE and ROBERTS, 1944]. As sea water freezes, a network of fresh-water crystals develops, forming pockets which contain salt water. The crystals grow at the expense of this brine, which becomes progressively heavier and more concentrated. Depending upon the temperature, this brine may or may not freeze, and even if it does freeze it thaws readily with rising temperature. Its high salinity and weight enable it to melt a path gradually downward through the ice, and the flushing-out process is facilitated by rising temperature and thawing. In this manner salt-water ice becomes fresh and changes from greasy, streaky and opaque to more or less granular, brittle, and clear, as well as increasing in strength. Hummocking hastens the freshening process by providing cracks for drainage and by lifting the ice above its surroundings so that the brine flushes out more easily.

Arctic sea ice contains three to ten per cent air, and fresh-water or brackish-water ice contains about two per cent air. Small air bubbles are spherical, but many of the larger ones are elongated vertically into thread-like tubes. Different horizontal layers of ice may contain differing amounts of air. Usually ice formed quickly or in rough weather contains more air than that formed slowly or in quiet weather [BAJKOV].

Several high-pressure forms of ice are known from laboratory studies, but none has been found in nature [DORSEY, 1940, and SELIGMAN, 1936].

Strength of ice--The strength of ice is dependent upon a wide variety of conditions, some of which will be treated following a simplified consideration of the thickness of ice required for aircraft landings.

Several empirical rules concerning the thickness of ice able to support various loads have been developed. Unfortunately, these do not usually specify the nature of the ice, its conditions of formation, or its environment. A familiar example of such rules are those stating that two inches of ice is considered safe for infantry, four inches for cavalry or light guns, six inches for heavy field guns, and eight inches for loads on sledges weighing not over 1000 lbs per square foot. Blind application of such empirical rules may lead to trouble. The Russians have done considerable work with the loading strength of ice and landings of aircraft thereon. Much of the following material has been derived from their reports [BAJKOV, MOSKATOV, 1938 a and b].

If some data are already available on the various loads borne by ice of known character and thickness, they can be extrapolated, for the required safe thickness of ice is directly proportional to the square root of its tolerable load. Thus, if it is known in a specific locality that a certain thickness of ice, S_1, will bear a load, L_1, then by simple proportion the thickness, S_2, needed to carry a load, L_2, can be calculated as:

$$S_2^2/S_1^2 = L_2/L_1 \text{ or } S_2 = \sqrt{L_2S_1^2/L_1} \; \ldots\ldots\ldots\ldots \; (2)$$

For aircraft landings, both the static load of the plane and the dynamic load or impact at time of landing must be considered. The usual Russian practice is to take six times the static weight of the plane as safely equivalent to these loads combined. Therefore, to obtain the thickness of ice necessary for a plane landing from data for static loads the formula will be

$$S_2 = \sqrt{(S_1^2 \times 6W_p)/L_1} \; \ldots\ldots\ldots\ldots \; (3)$$

in which W_p is the static weight of the plane. If the thickness of ice for landing of a plane of specified weight is already known, the formula can be used in the form first given.

It is known that fresh-water ice is about three times as strong as salt-water ice. This introduces a factor $\sqrt{3}$ in the formula for converting data from fresh-water ice to salt-water ice, thus:

$$S_s = 1.732\sqrt{(S_{fw}^2 \times L_2)/L_1} \; \ldots\ldots\ldots\ldots \; (4)$$

in which S_s = thickness of sea ice; S_{fw} = thickness of fresh-water ice.

From various accumulated data the Russians have developed the following simplified formulas for landings of aircraft with skis:

$$\left.\begin{aligned} S_r &= (15/4)\sqrt{W_t} \\ S_\ell &= (27/8)\sqrt{W_t} \\ S_s &= (27/4)\sqrt{W_t} \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

S_r is the thickness of river ice, S_ℓ of lake ice, and S_s of sea ice, in inches, and W_t is the weight of the plane in tons. These formulas apply to ice formed at or below 16°F. For ice formed at higher temperatures the thicknesses should be about 25 per cent greater. Lake ice is generally about ten per cent stronger than river ice. Probably no airplane, even the lightest, should attempt to land on fresh-water ice less than six inches thick. The S_s in the third formula above is for old sea ice, which is stronger than young sea ice. The required thickness of young sea ice is about three times that of river ice.

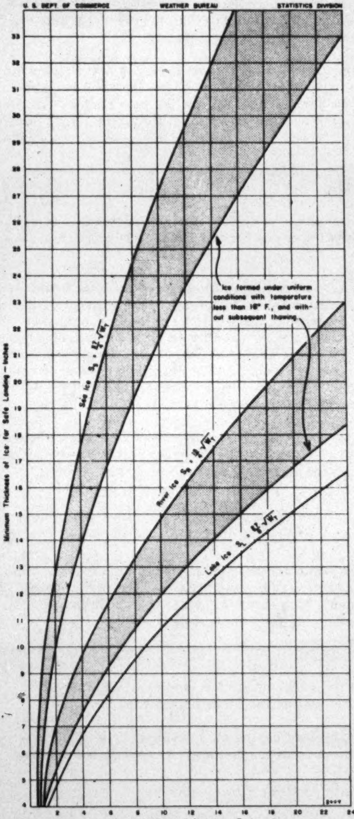

Fig. 3--Minimum thickness of ice required for safe landings of aircraft on skis [after U. S. Weather Bureau]

The curves of Figure 3 have been constructed from the above formulas. For planes on wheels the ice thickness should be about 20 per cent greater. Allowances must be made for major cracks and other structural weaknesses.

The above data can be checked by the following theoretical calculations. It is known that a roughly circular area with a radius of about 30 meters bears the load of an object the size of an aircraft on the ice surface. On this basis Formula (6) may be used to determine the ice thickness required for a specified load:

$$S_b = (18KP/\pi T^2)(1 - 2r_o/3r) \ldots . (6)$$

in which S_b is the maximum breaking strength taken as 30 kg/cm^2 for fresh-water ice and 15 kg/cm^2 for salt-water ice; K is a coefficient taken at 0.5; r is the radius of a circular plate bearing the load taken at 30 meters; r_o is the radius of circle upon which the load is concentrated--this is the size of the skis calculated as a circular area; P is weight of the plane in kg; and T is necessary thickness of ice for safe landing, in centimeters.

Substituting the figures for river ice and rearranging we get

$$T_r = \sqrt{3 \times 0.5[1 - (2r_o/3r)]6P/3.14(30)} \ . (7)$$

This can be simplified, since $(1 - 2r_o/3r)$ can be taken as unity. Then $T_r = 0.31\sqrt{P}$. This gives thickness of river ice in cm with weight of plane in kg, or $T_r = 3.68\sqrt{P}$ gives thickness in inches with weight in tons. This is very close to the $S_r = 15/4\sqrt{W_t}$ given above, as 15/4 = 3.75. Thus the theoretical and analogical methods check.

Salt makes ice plastic and weak [BRUCE, 1911], and sea ice becomes stronger as it freshens in the manner previously described. Newly formed sea ice less than six inches thick may bend under the weight of a man [BROWN, 1927]. It is probably unsafe for heavily loaded sledges and obviously unsuited for plane landings. Most sea ice has a breaking strength of ten to 15 kg/cm^2 in contrast to the 30 kg/cm^2 of fresh-water ice [MOSKATOV, 1938 a and b]. The crushing strength of ice ranges from 327 to 1000 lbs/in^2 and increases as the temperature falls, increasing four times between 23°F and - 76°F [BAJKOV]. Falling temperature, however, leads to contraction and cracking of ice and may weaken an ice layer even though water rises in the cracks and seals them. The tensil strength of ice is about one-third its crushing strength. Vegetation included within the ice makes it weaker.

Ice covered with a thick layer of snow is weaker because it is warmer, and ice becomes much weaker in spring for various reasons treated in more detail elsewhere. An abundance of parallel thread-like air bubbles in some ice decreases its strength considerably.

Ice shows the phenomenon of elastic fatigue and will bend or sag under continual stress [HAYES, 1937]. Constant travel of heavy loads over ice causes fatigue and further weakens it by opening and widening cracks. A fast-traveling plane on take-off or landing sends a wave through the ice before it and is followed by another wave. These waves cause fatigue and set up stresses which can be released by boring small holes through the ice [HAYES, 1937]. Heavily used runways on ice should be given frequent rest periods to allow recovery from fatigue and sealing of cracks.

Role of snow--Snow is important with regard to aircraft landings on frozen water bodies because more often than not it constitutes the surficial material. Since it is an excellent insulator it also exerts considerable influence on the rate at which ice forms and the thickness attained.

A common assumption in the North is that heavy snow in the fall means a rapid break-up in spring.

Snow constitutes an extra load on the ice and keeps it warmer, therefore weaker. These disadvantages are partly offset if the snow is well packed. Hard-packed snow does not retard the growth of ice nearly so much as loose snow and has a considerable bearing strength of its own. Wind-packed snow without benefit of thaw may have a bearing strength between 100 and 200 lbs/in^2 [BAJKOV]. Firm, wind-packed snow of this type is found chiefly in unforested northern areas where strong winds prevail. In such areas the snow tends to be firmly packed throughout, not just on the surface. In other regions a surficial crust on soft fluffy snow may give a misleading impression of the strength of a snow cover.

The snow on areas of ice to be used frequently for landings should be scraped or rolled. Scraping allows a greater thickness of ice to develop, but rolling is preferred in some quarters, possibly because of the bearing strength of firmly-packed snow, or because of unevenness in the underlying ice. In one instance the ice under an area scraped six days before was 16 inches thick and that under a nearby uncleared area was only 12 inches [HAYES, 1937]. Air temperatures during this period are not known. Another good reason for clearing snow from the ice is the prevention of slush formed if water gains access to the snow through cracks or by other means. Several inches of ice are destroyed by formation of the slush, which refreezes slowly even at air temperatures well below zero [HAYES, 1937]. If the snow cover is very thick, water forced up through holes and cracks in the ice forms a layer of slush with the lowermost snow which is entirely hidden by the overlying unaffected snow [DEPARTMENT OF NATIONAL DEFENSE, 1944]. The potential dangers of this situation are obvious. A snow cover on ice constitutes a further hazard by hiding weak spots which might otherwise be apparent from the air. Weak spots in the ice on inland water bodies can sometimes be identified by animal tracks leading up to but not across them. In any case the snow should be cleared from an area larger than that actually needed for operation, so that cracks and holes in the nearby ice have a chance to freeze. Snow should not be piled close to the runway, as it weakens the ice. If the surface of the ice beneath the snow is rough, scraping is obviously out of the question.

Even loose powdery snow changes progressively throughout the season without benefit of thawing. It becomes more granular and better packed. The increase in grain size is due to condensation of moisture from the atmosphere and the transfer of vapor from the vicinity of small grains to larger grains where ice is deposited. This takes place because the vapor pressure around ice grains is inversely proportional to the radius of curvature and is higher around small grains than large ones [SELIGMAN, 1936]. The surface of snow in wind-swept regions, although firm, is often rough in detail, owing to the formation of drifts, barchans, and sastrugi. Sastrugi are small ridges of hard-packed snow up to two feet high and ten to 15 feet long arranged parallel to the prevailing wind direction. They are capable of upsetting almost any plane on wheels or skis. Barchans are similar ridges lying transverse to the wind.

Nature of ice surface--The rough surface on sea ice more often limits its use for aircraft operations than thickness or strength. The surface of river and lake ice is usually smoother. Much sea ice is broken, rafted, pushed into hummocks and cracked by tides, winds, and currents in such a way as to make it wholly unsuited for aircraft operations. The open ice pack of summer consisting of separate ice fragments is obviously unsuited for aircraft landings unless some of the floes are exceptionally large. In winter much of this open pack refreezes with a surface that is too rough for aircraft landings until covered with snow. This is true in many of the fiords of East Greenland [WATKINS, 1932]. The closed pack may be suitable both winter and summer, although one polar flier has estimated that fully 90 per cent of the Arctic ice pack is unsuitable for aircraft landings [BYRD, 1928]. However, there have been many successful landings and take-offs from the Arctic pack, and suitable areas can usually be found [MOSKATOV, 1938 b, and ZUBOV, 1940]. Along low lagoon-fringed Arctic shorelines, like the north coast of Alaska, large areas of smooth flat ice are available for winter landings [WILKINS, 1928 a and b].

Springtime melting can make an ice surface very rough. Salty sea ice becomes soft and honeycombed in spring even though the air temperature remains below freezing [DEPARTMENT OF NATIONAL DEFENSE, 1944]. It is advisable to avoid areas of ice covered with melt water because the surface beneath is likely to be pitted and rough. However, it is true that melt water standing on ice is an indication of the soundness of that ice. As thawing progresses the water disappears into the ice, indicating that it is honeycombed and therefore weak and unreliable [DEPARTMENT OF NATIONAL DEFENSE, 1944]. After the melt water runs off, the ice surface is dry, white, soft, and sticky. Sometimes in spring, water on the ice refreezes surficially, leaving a layer of slush beneath. This bad condition is to be expected following a cold snap during break-up.

Fresh water, particularly in lakes, freezes to a firm smooth surface, but rivers may have areas of very rough ice if the current is swift and early ice has been broken up prior to final freezing. Ice on rivers may be dangerously thin over areas of fast-flowing water because of erosion on the underside. The surface on newly formed sea ice is sticky even at low temperatures, and sledges, skis, and other sliding surfaces do not move over it easily [BRUCE, 1911]. The Russians have been able to produce smooth surfaces on some areas of ice by pumping water onto the surface. This is likely to be unsatisfactory if the snow cover is at all heavy, for the snow and water form a slush which freezes slowly.

Melting and breakup--Ice and snow are melted by radiation from the sun and by heat conduction from the air, rocks, and water. Another less commonly recognized mode of melting is by condensation of warm moist air. This can be an important factor, for the moisture so condensed melts up to 7-1/2 times its own weight in snow [LIGHT, 1941].

Heat is more readily transferred through air by eddy diffusion than by molecular conduction. Thus, melting is likely to be greater with a wind than with calm air, and moist wind is a better melting agent than dry wind of the same temperature because of the melting caused by condensation. Cooling by evaporation in the case of dry wind helps to make it less efficient as a melting agent. Pressure facilitates melting by lowering the melting point, but below - 7.°6 F (- 22°C) pressure will no longer cause melting.

In spring, as the snow on the surface melts, the ice is covered with water. With continued thawing the ice becomes honeycombed with passages and holes into which the surface water drains.

Sea ice less than a year old is still somewhat salty and melts more readily than the older salt-free floes. It also honeycombs extensively as it melts. In spring, land-fast sea ice usually melts first near shore because of the relatively warm water which runs onto it from the land. Wind, waves, currents, and rivers aid break-up and melting by mechanical means.

In spring, lake ice "candles." That is, it separates into long pencil-like crystals by melting of intercrystal films [BUCHANAN, 1908]. These crystals slide past each other easily, and ice two feet thick may not bear the weight of a man. In spring, extreme caution must be used in making aircraft landings on lakes.

Break-up on rivers usually occurs three or four weeks after the mean air temperature has risen above 32°F. Ice on lakes breaks up two or three weeks later, and sea ice may break up about this same time.

Operations on ice--Landings on ice are easier to execute than take-offs owing to unevenesses in the ice surface. Planes operating on crusted snow should be careful not to break through the crust in turning.

Frequent measurements of ice thickness under and around a landing area should be made in spring, or even daily throughout the period of operation if the ice overlies flowing water. Measurements can be made by boring a hole through the ice with an auger. The lower part of such a hole is likely to be cone-shaped, so a hook or L-shaped rod should be used to measure thickness of the ice adjacent to the hole [HAYES, 1937]. Measurements made directly in the hole are likely to be in error. The breakup may be preceded by a rapid thinning of the ice, though break-ups can and do occur without any great amount of previous thinning. In high Arctic latitudes ice airdromes could be operated the year around, but any heavily used runway on ice should be given frequent periods of rest to permit recovery from fatigue and sealing of cracks.

Other things to be kept in mind are the notoriously poor depth perception in snow-covered terrain, and the tendency of skis to freeze immediately to ice or snow.

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METHODS USED IN ESTIMATING THE GROUNDWATER SUPPLY IN THE WICHITA, KANSAS WELL-FIELD AREA

Charles C. Williams and Stanley W. Lohman

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Abstract--This paper presents the methods used in studying the groundwater hydrology of an area in Harvey and Sedgwick Counties, Kansas, from which the city of Wichita derives its water supply. A summary of the data available for study is presented and several hydrologic factors are evaluated. The relationship between groundwater levels and precipitation is shown, and recharge is estimated. The effect of pumping on water levels is shown graphically, and the quantity of water withdrawn from storage is estimated from several water-table contour maps. The data are analyzed and the quantity of water available for pumping is estimated.

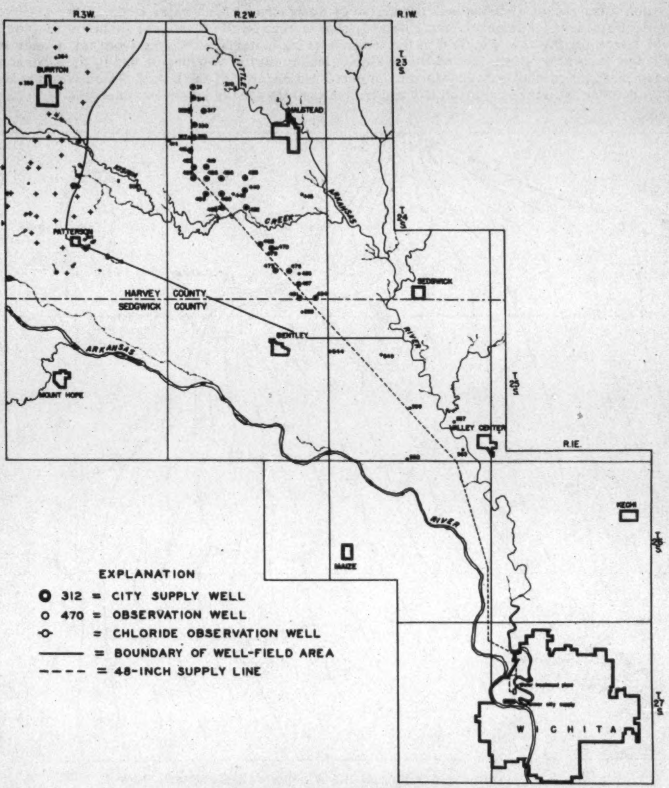
Introduction--Investigation of the geology and groundwater resources of an area comprising 2340 sq mi in south-central Kansas, which includes the new well field of the city of Wichita, was begun in July 1937 by the United States Geological Survey in cooperation with the State Geological Survey of Kansas, the Division of Sanitation of the Kansas State Board of Health, and the city of Wichita. Studies in this area by LOHMAN and FRYE [see "References" at end of paper, 1940] led to the location, in 1939, of a new source of water supply for the city of Wichita. This supply comes from 25 large-diameter, gravel-walled wells constructed by the city in 1939 and 1940 (see Fig. 1) and put into service September 1, 1940.

In the summer of 1940 the observation-well program was intensified in and near the new well field. Analysis of accumulated data available from observation-well measurements and pumpage records was begun in 1943, and a summary of the results of this study was prepared in 1945 for the period from June 1, 1940 to January 1, 1945. A report presenting all of the data collected during the course of this investigation is nearly completed and will be published as a Bulletin of the State Geological Survey of Kansas. Description of observation wells and water-level measurements are given in United States Geological Survey Water-Supply Papers 840, 845, 886, 908, 938, 946, 988, and 1018, and pumpage from the Wichita well field is given in Water-Supply Papers 946, 988, and 1018. It is the purpose of this paper to present some of the data collected and the methods of analysis employed in making estimates of the quantity of water available for pumping in the Wichita well-field area.

Geologic and hydrologic setting

The new Wichita municipal well field is located west and southwest of Halstead, Kansas, as is shown on Figure 1. The location of the well field was the result of a compromise in order to secure the maximum quantity of water of the best possible quality, with the least danger of contamination by oil-field brine. This area is underlain by unconsolidated deposits of silt, sand, and gravel of Pleistocene and Recent age. Geologic studies have led to the conclusion that a large stream flowed southward through McPherson County just north of this area, passed through the well-field area, and continued southward a short distance west of Wichita. It appears that this stream was joined at a point southwest of the well field by a large tributary stream which flowed southeastward south of the present Arkansas River. These Pleistocene stream deposits range in thickness from about 100 to 260 ft in the well-field area, and are somewhat thicker west of this area. Relatively impermeable shale of Permian age underlies the unconsolidated water-bearing deposits.

The depth to water ranges from about five ft to 25 ft below land surface in this area, but is from ten to 15 ft below land surface in most parts of the well field. The slope of the water table in the well-field area is southeastward toward the Little Arkansas River under non-pumping conditions. The Arkansas River is a perennial stream, and at normal stages is in approximate equilibrium with the groundwater reservoir (see Fig. 2). The Little Arkansas River is a perennial gaining stream throughout the area.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ARKANSAS
MOUNT HOPE
RIVER
VALLEY CENTER
KECHI
RIVER
MAIZE
W I C H I T A
EXPLANATION
312 = CITY SUPPLY WELL
470 = OBSERVATION WELL
= CHLORIDE OBSERVATION WELL
= BOUNDARY OF WELL-FIELD AREA
= 48-INCH SUPPLY LINE

Fig. 1--Map showing the location of the new Wichita well-field area, city-supply wells, and observation wells

Normal annual precipitation at Sedgwick, the United States Weather Bureau station nearest to the Wichita well field, is 29.47 inches. The greatest annual precipitation of record was 42.85 inches in 1927, and the least recorded annual precipitation was 16.93 inches in 1936. The average annual precipitation at Sedgwick for the six-year period from 1939 to 1944, inclusive, was 34.32 inches.

Quantitative estimates

The base data from which conclusions concerning water supply were drawn consist of (1) logs and well cuttings from 19 cable-tool test wells, from 40 rotary test holes, and from 25 city-supply wells; (2) records of water-level fluctuations in ten observation wells in the general well-field area, selected from a large number of observation wells after study of the water-table fluctuations revealed that they are representative of that part of the well-field area not in the immediate area of pumping influence (see Fig. 3); (3) records of water-level fluctuations in six observation wells located about one-half mi from the pumped wells (see Figs. 5 and 6), in 25 wells located 500 ft from the pumped wells (see Fig. 6), and in 25 wells located 100 ft from the pumped wells (see Fig.

6), which were chosen as being representative of fluctuations of the water table in the area of pumping influence; (4) pumpage data obtained from meters on the municipal supply wells (see Fig. 6); (5) values for the specific yield of the water-bearing materials obtained from tests made in the hydrologic laboratory of the United States Geological Survey in Washington and in the laboratory at Lawrence; (6) rainfall data obtained from published records of the United States Weather Bureau; and (7) determinations of permeability and transmissibility made by several methods.

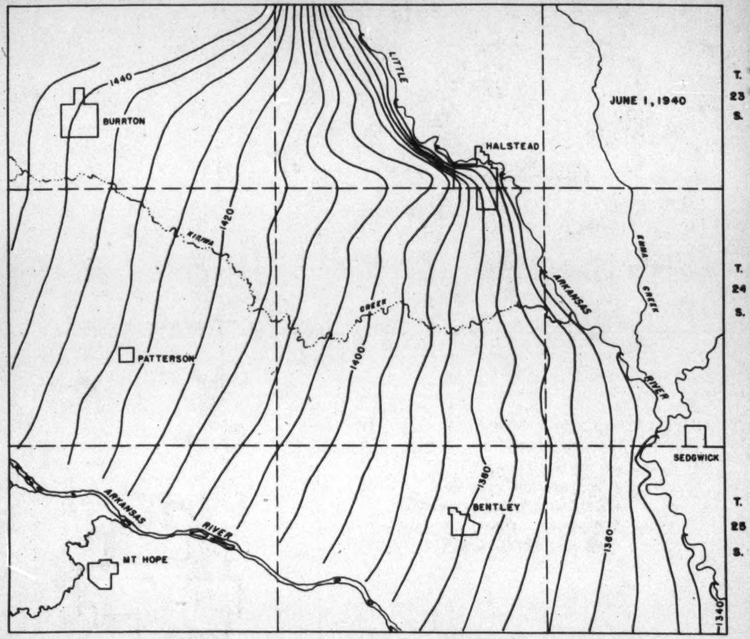

Fig. 2--Water-table contour map of the Wichita well-field area, June 1, 1940

In addition to these data, a series of 13 water-table contour maps have been prepared, based on periodic water-level measurements in about 190 wells. The first of these maps (see Fig. 2) was prepared from measurements made in June 1940, before pumping began, and three additional maps were made each year since pumping began. The last water-table contour map is shown in Figure 8. Maps showing lines of equal change in water level also were prepared by comparing water-table contour maps for each period after pumping began with the one prepared from measurements made before pumping began. The final map of this type is shown on Figure 9.

Estimate of specific yield--Most of the quantitative estimates of water supply made for this area are contingent, in part at least, on estimates of the specific yield of the water-bearing materials in the zone of water-table fluctuation and in the zone of saturation.

During the course of the investigation which led to the location of the new well field, many cable-tool and rotary test holes were drilled and samples of the materials penetrated were collected carefully. The specific yield of some of the samples from cable-tool test holes was determined indirectly by first determining the moisture equivalent to ascertain specific retention; the moisture equivalent was then adjusted by applying the proper factor [PIPER, 1933] and subtracted from the porosity to obtain the value of the specific yield. The porosity and moisture-equivalent determinations were made in the hydrologic laboratory of the United States Geological Survey.

Additional samples were collected from holes bored by hand auger near the key observation wells in the well-field area. These samples were collected following a period of about three weeks when there had been no precipitation, and it is believed that they were taken just above the capillary fringe. The samples were weighed, carefully dried, and reweighed to determine the specific retention. Porosity and apparent specific gravity were then determined and the value of the specific yield was calculated. The average specific yield of samples collected from the zone of water-table fluctuation in this area was found to be 25.2 per cent. The average specific yield of samples taken from points below the water table was 27.8 per cent. The average specific yield of all the samples collected and studied from this area was 26.8 per cent. The specific yield of the samples ranged from eight to 38 per cent.

Estimate of recharge, inflow--The coefficient of transmissibility, as defined by **THEIS** [1935] and the coefficient of permeability, as defined by **MEINZER** [**STEARNS**, 1927] were determined by pumping tests at wells and by analysis of samples collected from test drilling.

The coefficient of permeability was determined for many samples in the hydrologic laboratory in Washington and in the field laboratory at Wichita. The weighted average coefficients of permeability were computed for the entire thickness of the saturated material penetrated in each well by the cable-tool test drill, and these averages ranged from 210 to 830 in the Wichita well-field area.

Pumping tests were made at each of the 25 wells in the well field and the coefficients of transmissibility determined by the recovery method ranged from 46,000 to 330,000, and the average coefficient of transmissibility was computed to be about 124,500. Using the coefficients of transmissibility determined from the pumping tests and the natural gradient of the water table (see Fig. 2), the quantity of water moving across the boundary of the Wichita well field under non-pumping conditions was calculated and found to be about 5,300,000 gallons a day.

As noted above, two observation wells are located 100 ft and 500 ft from each pumped well, and water levels in these observation wells were measured periodically during the pumping test at each well. The observation wells do not penetrate the entire aquifer and are screened at the bottom only. For these and other reasons the application of the Thiem method was not considered advisable. However, using data shown on Figure 6, the difference in average draw-down in the wells 500 and 100 ft from the 25 pumping wells at the end of 1944, and the average pumping rate in 1944, the average transmissibility was calculated to be about 250,000 using the Thiem method. Comparison shows that this value is about twice the average value obtained by the recovery method. We believe that (1) the Thiem method probably is not applicable to the data available in this area; and (2) the results obtained using the recovery method may be in error, and if so, probably indicate too small a quantity of water moving into the well field.

Recharge from precipitation--The effect of precipitation on water levels in observation wells was studied and numerous hydrographs were analyzed in order to estimate the quantity of water added to the groundwater reservoir from rainfall on this area. The hydrographs of well 557 and the average water level in ten wells (numbers 358, 445, 502, 511, 544, 549, 557, 558, 560, and 563) are shown on Figure 3. The ten wells numbered above are measured monthly and were referred to an arbitrary datum and given a stage of ten ft above datum on December 1, 1938. The ten wells were chosen primarily for their length of record, freedom from observable effects of pumping, and geographic location with reference to the new Wichita well field. These wells are believed to represent nearly average non-pumping hydrologic conditions in the well-field area. Well 557 is equipped with an automatic water-stage recorder.

A tendency toward a rather close correlation between the two hydrographs and between the hydrographs and the graph showing cumulative departure from normal precipitation is observable in Figure 3. There are some lags observable in the hydrograph as compared to the rainfall graph and the magnitude of the rises and declines apparently is not constant in the two curves; however, the trends are comparable. The correlation is good and the curves are nearly the same through the years 1938 to 1942 inclusive. During 1943 precipitation was approximately normal, but was not great enough to maintain water levels at the high stages attained previously, and the graphs show that groundwater discharge exceeded groundwater recharge. In 1944 precipitation at Sedgwick was 144 per cent of normal and water levels rose again, reaching record high stages in May; indeed, water levels in some wells were near the maximum possible stage. During the last part of 1944 discharge again exceeded recharge, and although precipitation was greater than normal during this period, it was not great enough to maintain the exceptionally high stages attained in May.

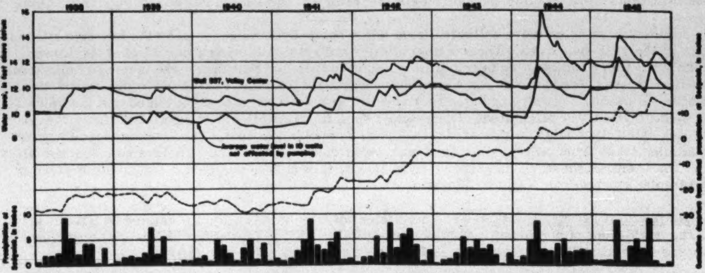

Fig. 3--Hydrographs showing the fluctuations of water level in well 557, near Valley Center, the average water level in ten wells in the Wichita well-field area not affected by pumping, the cumulative departure from normal monthly precipitation at Sedgwick, and the monthly precipitation at Sedgwick

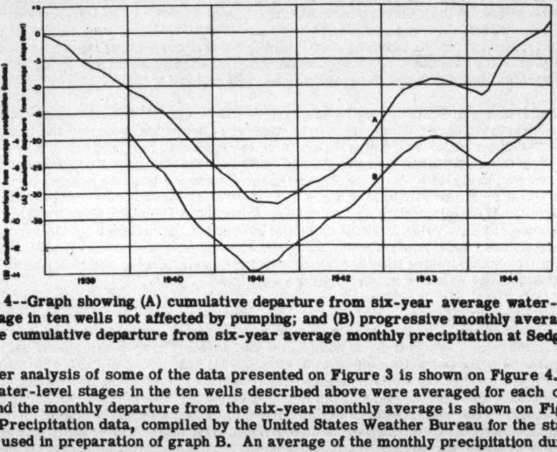

Fig. 4--Graph showing (A) cumulative departure from six-year average water-level stage in ten wells not affected by pumping; and (B) progressive monthly average of the cumulative departure from six-year average monthly precipitation at Sedgwick

Further analysis of some of the data presented on Figure 3 is shown on Figure 4. The average monthly water-level stages in the ten wells described above were averaged for each of the twelve months, and the monthly departure from the six-year monthly average is shown on Figure 4 as graph A. Precipitation data, compiled by the United States Weather Bureau for the station at Sedgwick, was used in preparation of graph B. An average of the monthly precipitation during the same six-year period as shown on graph A was calculated, and the progressive monthly average of the cumulative departure from this six-year average is shown on graph B. This method of analysis eliminates effects of seasonal and other variations in precipitation and illustrates the progressive and continuing correlation between variations in amount of precipitation and fluctuations in groundwater level.

As noted above, the average specific yield of the water-bearing material in the vicinity of the Wichita well field is believed to be about 25 per cent by volume. If this value is nearly correct, a rise of water level of one ft in a well represents a net addition of three inches of water to the underground reservoir. An analysis of net recharge as computed from the record of water-level fluctuations in well 557 in relation to precipitation is given in Table 1. Calculations of the values given in column (6) indicate that the quantity of precipitation which is measurable as net recharge has averaged about 20 per cent during the seven years of record. It is believed that the computed percentage of net recharge (54.8 per cent) in 1944 is too large, because at exceptionally high stages the water table fluctuates through material having a permeability lower than that of the material through which the water normally fluctuates. If the figures given in Table 1 are nearly correct, the measurable average annual net recharge (20 per cent of normal rainfall) is about six inches of water or about 320 ac-ft on each sq mi. This value, if correct, is the minimum quantity, because recharge during periods of declining water level and discharge during periods of rising water level have not been taken into account.

Table 1--Relation of cumulative rise in water level in well 557 to annual precipitation at Sedgwick

Year	Annual precipitation (1)	Annual cumulative rise in water level		Cumulative annual precipitation (4)	Accumulated cumulative rise in water level	
		Water (2)	Percentage of annual precipitation (3)		Water (5)	Percentage of cumulative precipitation (6)
	in	in	pct	in	in	pct
1938	35.42	8.25	23.3	35.42	8.25	23.3
1939	25.16	5.10	20.3	60.58	13.35	22.0
1940	29.55	2.82	9.6	90.13	16.17	18.0
1941	38.71	10.05	26.0	128.84	26.22	20.4
1942	41.45	8.25	19.9	170.29	34.47	20.2
1943	29.05	2.58	8.9	199.33	37.05	18.6
1944	42.55	23.34	54.8	241.88	60.39	24.9
1945	35.70	13.80	38.3	287.58	74.19	25.8

Colleagues in the Geological Survey have discussed with the authors some of the sources of error inherent in the methods of analysis outlined above, and have advised caution in ascribing rise and fall of the water table as measured in wells to groundwater recharge and discharge until the mechanics of the capillary fringe have been studied further. However, it is believed that inaccuracies of interpretation of water-level fluctuations caused by imperfect knowledge of capillary phenomena are minor when records of sufficient length and continuity are considered.

The effect of pumping on water levels--Pumping from the 25 city-supply wells comprises the greater part of withdrawal of ground water in this area. The quantity of water pumped during the period from September 1, 1940, to January 1, 1945, was 23,284 million gallons, an average of 448 million gallons a month or about 15 million gallons a day. The quantity of water pumped has ranged from 248 million gallons in February 1941 to 653 million gallons in July 1943 and August 1944. Hydrographs showing the fluctuations caused by pumping and by natural processes, together with graphs showing the quantity of water pumped from the city wells and the precipitation at Sedgwick are shown in Figure 5. Well 448 is located near the center of the well field and is affected by the pumping of several nearby wells; well 568 is located about one-half mi south of the south end of the well field and is affected by the pumping of wells 491 and 494 only. Six wells including the two above (numbers 327, 414, 448, 470, 486, and 568 in Figure 1), which are located

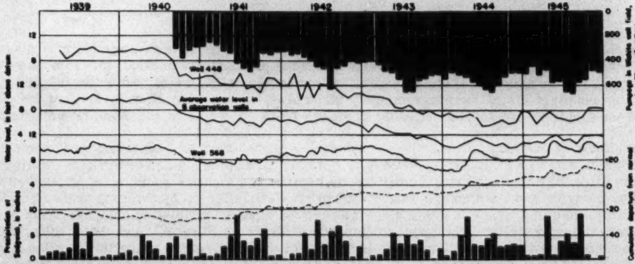

Fig. 5--Hydrographs showing the fluctuations of the water levels in wells in the Wichita well-field area, pumpage from the well field, monthly precipitation at Sedgwick, and cumulative departure from normal precipitation at Sedgwick an average of about one-half mi from pumped wells and hence are affected by pumping were selected for study and the hydrograph of the average monthly water level in these wells is shown on Figure 5. From September 1, 1940, to January 1, 1945, the water level in well 448 declined 7.99 ft, the average water level in six wells affected by pumping declined 6.02 ft, and the water level in well 568 lowered 2.36 ft as the result of pumping from the city wells. The effect of recharge on the water levels in these wells appears to have been masked except in well 568, where the effect of pumping has been less than that of recharge, especially in 1942 and 1944.

At the time the 25 new Wichita city-supply wells were constructed, observation wells were drilled 100 ft and 500 ft from each well, and these wells were measured at regular intervals thereafter. The effects of pumping from the supply wells on the water level in these observation wells and on the water level in the six observation wells referred to above are shown on Figure 6, together with the monthly pumpage from the supply wells. The water levels in all of the observation wells were assigned a stage of ten ft above an arbitrary datum on June 1, 1939. The average monthly water level in six comparable observation wells located about one-half mi from the pumped wells, in 25 wells located 100 ft from the pumped wells, and in 25 wells located 500 ft from the pumped wells was computed for each of these three groups of wells, and a progressive average of the average monthly water level was calculated for each group, based on the year June 1, 1939, through May 31, 1940. Similarly, a graph of the progressive average of the quantity of water pumped each month from the city-supply wells was prepared, based on the year September 1, 1940, through August 31, 1941, the first year of pumping. The use of progressive averages results in smoother curves than those from data plotted directly and trends of water levels and pumpage are more readily discernible. The similar curves show that as the rate of pumping increased, the average water level in all of the wells declined and that this decline ceased toward the end of 1944 when the pumping rate became nearly constant. The graphs indicate that water levels in wells 100 ft, 500 ft, and one-half mi distant from the pumped wells probably will remain near the average levels attained at the end of 1944 and during 1945 if the rate of pumping remains nearly uniform.

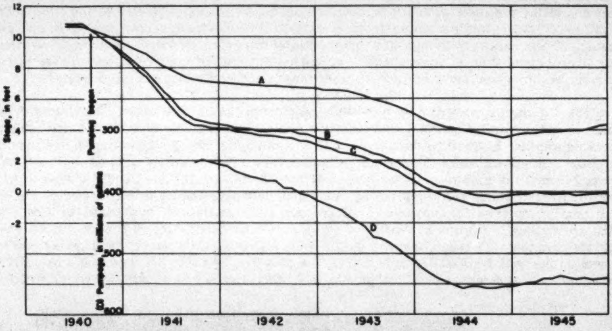

Fig. 6--Graphs showing one-year progressive averages of (A) The average monthly stage of water levels in six observation wells located approximately one-half mi from supply wells; (B) the average monthly stage of water levels in 25 wells, each located 500 ft from supply wells; (C) average monthly stage of water levels in 25 wells located 100 ft from supply wells; and (D) monthly pumpage from 25 wells in the Wichita well field

The effects of pumping on water levels shown on graphs above are superimposed upon natural fluctuations of water level caused by excess or deficient precipitation. In order to determine more nearly the effect of pumping alone, the difference between the average water level in ten wells not affected by pumping and the average water level in six wells affected by pumping was calculated, and this difference in average monthly stage was plotted against cumulative pumpage from the Wichita water-supply wells. The graph so obtained is shown on Figure 7, and shows the greater rate of lowering of water levels during the first year of pumping representing initial withdrawals from storage, the nearly stabilized condition of the water levels at the end of the third year of pumping, the increase in rate of pumping and corresponding decline in water levels in 1943 and 1944, the readjustment of water levels to the increased rate of pumping in 1944, and the apparent restabilization of water levels near the end of 1944.

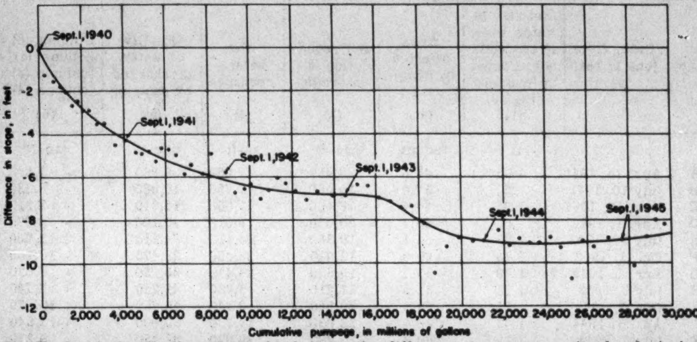

Fig. 7--Graph showing the relationship between the difference in average water levels in ten wells not affected by pumping and six wells affected by pumping, and the cumulative pumpage from the Wichita city-supply wells

Estimate of changes in storage--By "change in storage," as used here, is meant the net addition of water to or net withdrawal of water from the aquifer. In order to determine the magnitude of the withdrawal of ground water from storage, 13 water-table contour maps were prepared of the well-field area which represent hydrologic conditions before pumping began and at several dates since pumping began. The first of these maps is shown on Figure 2 and the final map considered here is shown on Figure 8.

The water-table contour maps were originally prepared at a scale of two in/mi with a contour interval of five ft. These intervals were later divided into five equal parts and contour lines having an interval of one ft were interpolated. By superimposing each map prepared after pumping began upon the map prepared before pumping began and by connecting points of contour crossings, lines of equal change in water levels, here called isometahydral lines, were drawn. The resulting 12 isometahydral maps have afforded a measure of the magnitude of change in groundwater storage for each of the periods between the several water-table contour maps.

An area of 85.3 sq mi bounded by the heavy line and the Little Arkansas River shown on Figure 1 was selected after study of logs of test holes, records of observation wells, and the several water-table contour maps as being about the maximum area which ultimately may be affected by pumping in the well field. Not all of this area had been affected by pumping at the end of 1944. The areas between successive isometahydral lines showing increases and decreases in groundwater storage were measured with a planimeter and the net increase or net decrease in storage within the area was determined. The map on Figure 9 shows the cumulative effects of pumping at the end of four years superimposed upon natural changes in water level. The data relevant to and obtained from each map are given in Table 2 and part of the data is shown graphically on Figure 10.

The net rise or net decline in water level from June 1, 1940, before pumping began, to the end of each map period in ten observation wells not affected by pumping is given in column (1) of Table 2. The areas affected by pumping during each period [column (2)], which were measured directly from large-scale isometahydral maps, are the areas in which the water table lowered more than, or did not rise as much as, the average water levels in the ten wells not affected by pumping.

The areas between each isometahydral line in the base area (see Fig. 1) were measured directly from each map, and the net volume of water-bearing material unwatered during the map period was calculated. The net volume of water withdrawn from storage in the base area [column (3)] was obtained by applying the factor for specific yield to the volume of the aquifer unwatered. The net natural recharge or net natural discharge which would have been measurable in the base area if pumping had not occurred is given in column (4). The magnitude of this quantity of water

Table 2--Data relative to changes in storage in the Wichita well-field area

Map	Date, from June 1, 1940 to:	Net rise in water level in ten wells not affected by pumping (Fig. 3) (1)	Area affected by pumping (2)	Net reduction in storage (3)	Net natural recharge (4)	Quantity of water discharged by pumping (5)	Column (6) = column (5) - [column (3) + column (4)] (6)
		ft	sq mi	ac-ft	ac-ft	ac-ft	ac-ft
A	Apr. 15, 1941	- 1.25	44.6	28,450	- 17,060	6,860	- 4,530
B	July 10, 1941	.57	57.0	10,530	7,780	10,080	- 8,230
C	Nov. 10, 1941	1.03	44.4	8,460	14,060	15,310	- 7,210
D	Apr. 1, 1942	.66	58.7	20,060	9,010	20,100	- 8,970
E	July 10, 1942	1.95	54.1	10,580	26,610	24,210	- 12,980
F	Oct. 1, 1942	2.10	65.8	12,910	28,660	28,470	- 13,100
G	Apr. 1, 1943	1.79	55.7	19,570	24,430	35,950	- 8,050
H	July 5, 1943	1.15	51.5	17,810	15,700	41,250	+ 7,740
I	Oct. 7, 1943	.23	55.2	29,940	3,140	46,750	+ 13,670
J	Apr. 1, 1944	1.05	56.0	28,030	14,330	55,900	+ 13,540
K	July 7, 1944	2.19	68.8	22,290	29,890	61,450	+ 9,270
L	Oct. 1, 1944	1.46	64.5	24,640	19,930	66,850	+ 22,280

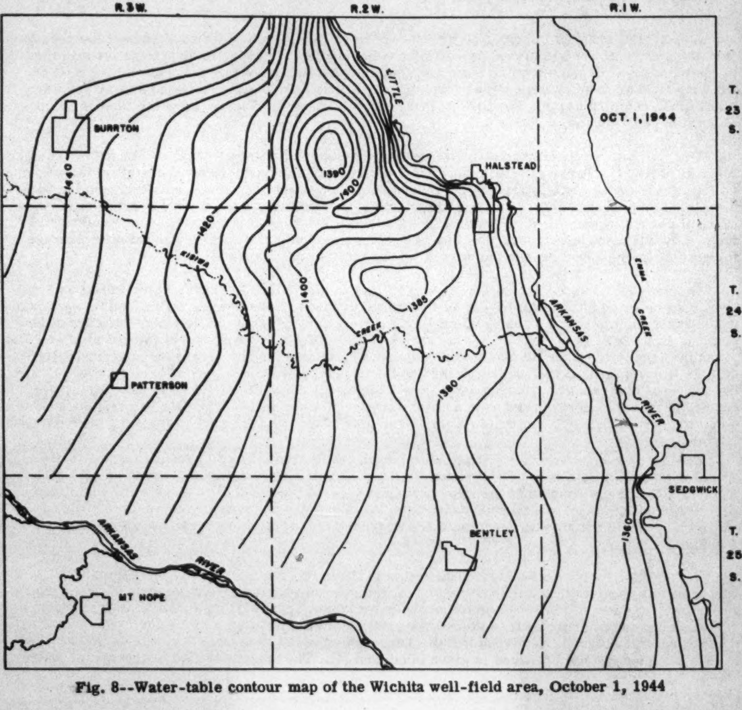
R.3W.
R.2W.
R.1W.
T. 23 S.
T. 24 S.
T. 25 S.
OCT. 1, 1944
BURRTON
HALSTEAD
PATTERSON
BENTLEY
SEDGWICK
MT HOPE
LITTLE
ARKANSAS
RIVER
EMMA CREEK
KISIWA CREEK
ARKANSAS RIVER
1440
1420
1400
1390
1400
1385
1390
1380
1360

Fig. 8--Water-table contour map of the Wichita well-field area, October 1, 1944

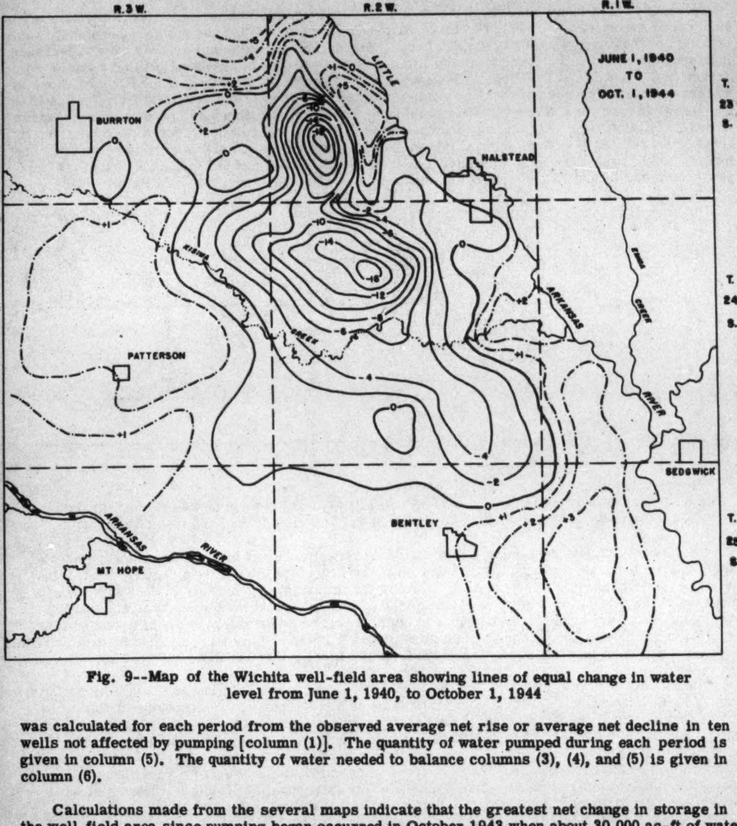

Fig. 9--Map of the Wichita well-field area showing lines of equal change in water level from June 1, 1940, to October 1, 1944

was calculated for each period from the observed average net rise or average net decline in ten wells not affected by pumping [column (1)]. The quantity of water pumped during each period is given in column (5). The quantity of water needed to balance columns (3), (4), and (5) is given in column (6).

Calculations made from the several maps indicate that the greatest net change in storage in the well-field area since pumping began occurred in October 1943 when about 30,000 ac-ft of water is calculated to have been removed from storage. After four years and one month of pumping, measurements indicate that the change in storage in the base area has been about 24,600 ac-ft.

Analysis of data--The values given in Table 2 and shown on Figure 10 do not balance, and an apparent discrepancy of considerable magnitude is given in column (6). One of the factors which may account for the lack of balance is the specific yield. Experimental determinations of this factor indicate that the true value is obtained only after the saturated material has been drained for a long period of time. If incomplete drainage is assumed during the first map period and the value for specific yield is changed from 25 to 15 per cent in the computations, the several columns in Table 2 balance. Similarly, if a sliding scale of values for specific yield ranging from 15 per cent to about 30 per cent is used for the other map periods, the measured and calculated volumes balance. It is believed that the laboratory determinations of specific yield, discussed above, are nearly correct, and that the apparent specific yield increased from about 15 per cent at the end of the first period studied to near the real or determined value of 25 per cent in later periods. The value for specific yield was probably about 19 per cent at the end of the second year of pumping and probably reached the real value sometime during the third year of pumping.

Measurements made from the water-table contour maps indicate no decrease in the average gradient of the water table along the Little Arkansas River from the time pumping began until the last part of the third year after pumping began. Measurements made in July 1943 show a decrease in average gradient of 1.8 ft/mi near the Little Arkansas River, in October 1943 there was a decrease of 2.1 ft/mi, and in October 1944 (see Fig. 8) there was a decrease of 2.6 ft/mi. There is no measurable difference between the gradients at the west side of the well field from June 1940 to October 1944 (see Figs. 2 and 8). It is concluded, therefore, that there was no measurable change in the quantity of water entering and leaving the well field by percolation through the aquifer until about July 1943. At this time about eight per cent of the quantity of water formerly being discharged into the Little Arkansas River was intercepted; by October 1943 and October 1944 it appears that about ten per cent and 12 per cent of this quantity was diverted toward the well field.

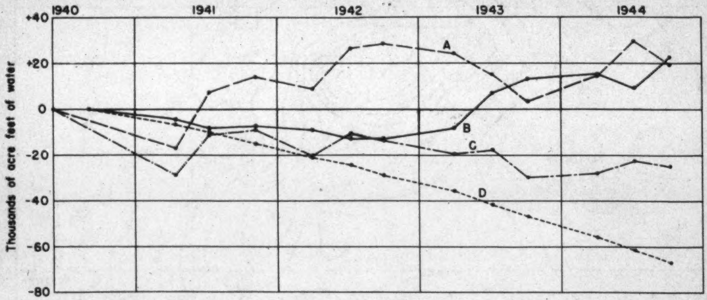

Fig. 10--Graphs showing (A) column (4) of Table 2; (B, and the area between B and the datum line) column (6) of Table 2; (C) column (3) of Table 2; and (D) column (5) of Table 2

On the basis of data pertaining to the physical properties of the aquifer, the slope of the water table, and the location of the well field relative to the Little Arkansas River, it is calculated that the water table must be lowered about 40 ft below the initial level before all of the water percolating toward the river in this section of its course can be intercepted and the gradient reversed toward the well field from the river. It is calculated that an additional quantity of water of the order of magnitude of 200,000 ac-ft must be removed from storage in the well field before hydraulic conditions are such that water can percolate from the Little Arkansas River toward the wells.

The amount of precipitation on the well-field base area was 160.41 inches during the period from June 1, 1940, to October 1, 1944. During this same period the quantity of recharge in this area, shown above to be about 20 per cent of the precipitation, was about 146,000 ac-ft; the quantity of water percolating toward the Little Arkansas River which was diverted by pumping was about 750 ac-ft; and of the 66,850 ac-ft of water pumped during the four years, about 44,600 ac-ft was derived from storage and about 22,200 ac-ft was derived from water which otherwise would have been discharged through natural processes (see Table 2). The total quantity of water which would have been discharged naturally from the well-field area during this period is calculated to be about 127,000 ac-ft and the quantity salvaged is about 17 per cent of this total. Measurements made from the map shown on Figure 9 indicate that the area affected by pumping at the end of the fourth year was about 65 sq mi. Other data given above indicate that the recharge on this area during the four years was about 83,200 ac-ft. If there had been no pumping 15,200 ac-ft of this recharge would have been added to storage beneath the 65 sq mi affected, and 68,000 ac-ft would have been discharged. Thus, if the 22,200 ac-ft of water salvaged from natural discharge was salvaged from the 65 sq mi affected by pumping, the quantity salvaged was about 33 per cent of the potential natural discharge from that area.

Estimate of quantity of water available for pumping--Using estimates and analyses of data outlined above, it is concluded that: (1) The water levels in wells affected by pumping in the well-field area apparently had become stabilized at the end of the first four years of pumping; (2) about one-third of the natural discharge in the area of pumping influence was being salvaged; (3) the Little Arkansas River remains a gaining stream; and (4) an additional large quantity of ground water must be removed from storage before the potential yield can be reached.

An estimate of the potential yield may be made from the calculations presented above. The maximum area of influence of the present well field is estimated to be about 85 sq mi, and it is estimated that recharge in years of normal precipitation will be about 27,000 ac-ft. When the water table is lowered to a depth sufficient that all natural recharge may be salvaged, percolation into the area, including influent seepage from the Little Arkansas River, will be at least 13,000 ac-ft a year. Thus, the potential perennial yield appears to be about 40,000 ac-ft a year, or about twice the present annual pumpage. Before a quantity of water equivalent to the potential yield can be added to the aquifer each year, about 200,000 ac-ft, must be removed from storage. This quantity is equivalent to the quantity which would be pumped in ten years at the present rate of pumping.

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EARTHQUAKES, SEPTEMBER TO DECEMBER, 1946

Ross R. Heinrich

An earthquake, recorded at the Instituto Geofisico de los Andes Colombianos on October 9, 1946 (iP $19^h56^m54^s$ U. T., S_n - P_n distance 120 km), was felt in Bogota as a weak tremor, reports J. E. Ramirez. The government of the U. S. S. R. reported that the destruction of the earthquake of November 2 (18^h28^m U. T., see Tables 1 and 2) was centered in the industrial districts of Namangan, Andizhan, and Fergana in Uzbek, and in the Dzhala Abad region of Kirghiz. Official sources said the earthquake caused civilian deaths and building destruction. According to B. Gutenberg the Pasadena records showed a magnitude of about 7-3/4. On November 10 slight tremors were felt in the vicinity of Yankton in southeastern South Dakota at about 09^h00^m U. T. No damage was reported. On November 10 a very destructive earthquake occurred in northern Peru (see Tables 1 and 2). The areas of greatest destruction were in the Andean departments of La Libertad and Ancachs. The mountainous country adjacent to and west of the Rio Marenon was especially affected. Preliminary estimates of the casualties were as high as 800 killed and 500 injured, with an untotaled number homeless as a result of the many structures destroyed. The following towns reported severe damage; Sihuas, Pomabama, Mollepata, Mollebama, Conchucos, Pampas, and Palta Bueno. The recorded magnitude at Pasadena was reported by B. Gutenberg as 7-1/2. This earthquake was followed by a series of aftershocks. The Central Meteorological Observatory of Japan reported that a mild earthquake was felt in Tokyo on November 15 (probably local date). The Observatory placed the epicenter in northeastern Tokyo Bay and assigned a depth of focus of 80 km. In a press dispatch released on November 16 the station recalled that "disturbances originating deep in Tokyo Bay preceded the great Tokyo earthquake of 1923 and warned 'the latest tremblor bears watching.'" A shock reported as "violent" but nondestructive was felt in Lima, Peru, on November 19. No detailed information was available as of January 1, 1947. A slight tremor which rattled dishes and windows was felt in Massena, New York, on November 24. W. A. Lynch writes that the vertical seismograph of the Fordham station recorded a slight tremor at $10^h22^m52^s$ U. T. An earthquake was "felt strongly" at Eureka, California, on December 18. Light fixtures swayed and dishes rattled. B. Gutenberg reported the following readings from Pasadena: P! $14^h22^m25^s$; S! $14^h24^m00^s$ U. T.

Table 1--Provisional epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.	Epicenter		Remarks
		Lat.	Long.	
1946	h m	°	°	
November 1	11 14.4	52 N,	174 W	South of Atka Island, Aleutian Islands
November 2	18 28.4	41 N,	76 E	Kirghiz, U. S. S. R.
November 3	19 32.5	0	16 W	Southwest of Liberia, Africa
November 4	21 47.6	40 N,	53 E	Near west coast of Turkmen, U. S. S. R.
November 10	17 42.8	9 S,	77.5 W	Near Sihuas, Peru, about 225 miles north of Lima
November 12	17 28.7	21 S,	173 W	. . .
December 20	19 19.0	33.3 N,	134.0 E	Near east coast of Shikoku Island, Japan
December 21	10 18.8	44 N,	148 E	Off east coast of Hokkaido Island, Japan

An extremely violent earthquake and a resulting tsunami caused widespread death and destruction on three of the main Japanese Islands on December 20. About 60,000 square miles of Honshu, Shikoku, and Kyushu were affected. Both the earthquake and the seismic sea wave caused damage, but apparently the latter wrought the most havoc. The earthquake, which had a submarine epicenter south of Tokyo, was felt over a wide area extending from Tokyo on Honshu to the Island of Kyushu. It is difficult in the preliminary reports to be certain of the real damage and to determine the extent and character of the earthquake damage as distinct from the tsunami destruction, since the apparently greater disaster of the latter is always emphasized. Fire was mentioned in several reports and may have been caused by the earthquake damage; for example, fire reputedly destroyed about one-third of Shingu on Honshu. Kyodo, Japanese press agency, reported at least 14 prefectures had widespread damage; Gifu, Osaka, Kochi, Kagawa, Shiga, Hyogo, Shizuoka, Nara, Oita, Tokushima, Wakayama, Mie, Okayama, and Aichi. At Kainan on Wakayama Peninsula south of Osaka and relatively exposed to the open sea, observers reported a great rumbling from the sea followed (possibly after an interval) by the first rush of water as the tsunami hit the city. Forty minutes later a second wave hit the city. In all, six waves were reported at many points. In Kainan the waves were said to be ten feet high; various heights of wave and depth of flood were reported. Osaka, at the head of a bay, reported flood water as deep as three feet in some sections. Early estimates of casualties (January 1, 1947) ranged from 600 to 1000 killed and up to 600 injured. Preliminary damage tabulations showed 7000 homes destroyed and 10,000 damaged, with about 25,000 structures temporarily inundated. About 2000 vessels were reported beached or swept out to sea by the waves.

Table 2--Tentative epicenters, Jesuit Seismological Association

Date	Time U. T.	Epicenter		Depth
		Lat.	Long.	
1946	h m s	°	°	km
September 23	23 30 04	4.2 S,	148.2 E	?
September 25	10 05 42	19.8 N,	70 W	....
September 29	03 01 55	4.8 S,	152.8 E	....
September 30	00 59 51	12.6 S,	75.8 W	almost 100
October 2	04 46 22	54.0 N,	159.7 E	?
October 2	06 43 30	54.0 N,	159.7 E	....
October 4	14 45 35	19.2 N,	68.9 W	50
October 22	10 00 41	22 S,	178 E	250
October 30	07 47 44	53.7 N,	163.3 W	50
November 1	11 14 30	51 N,	173.2 W	....
November 2	18 28 39	41.3 N,	71.2 E	100 ±
November 3	19 32 40	0	17 W	....
November 10	17 43 00	7.8 S,	77.8 W	....

The epicenter of the main earthquake, which was recorded by seismograph stations throughout the world, has been provisionally located by the United States Coast and Geodetic Survey at 33°.3 N, 134°.0 E, origin time $19^h19^m.0$ U. T. B. Gutenberg reports that the magnitude on the Pasadena seismograms was 8-1/4. For a recent discussion of Japanese earthquake phenomena confer N. H. HECK [see "Reference" at end of report, 1944]. Two slight earth disturbances which awakened residents were reported from a limited area in west St. Louis and St. Louis County, Missouri, on January 4, 1947 (11^h00^m and 11^h40^m U. T.). Observers described the disturbances, particularly the second one, as like a boiler explosion in the basement and like snow and ice falling off the roof (there was a snow cover present from precipitation on the three previous days). The Wood-Anderson seismographs at St. Louis recorded a very small disturbance at $11^h42^m40^s$. The character of this record was unlike any of the ordinary blasts and earthquakes regularly recorded at this station. Only one phase (impetus) was recorded, and so P and S phases were not interpretable for distance. The recorded phase has certain characteristics suggestive of a shear or surface wave. The phenomenon might be readily passed over as an exceptional oddity were it not for the fact that several similar disturbances have been recorded and felt in the past few years. Although no identification of a source has been made, there is some reason to believe that the source may be artificial. Proof of the natural or artificial source of these disturbances may furnish some interesting seismic data.

The epicenters listed in Tables 1 and 2 have been determined by the United States Coast and Geodetic Survey and the Jesuit Seismological Association cooperating with Science Service and a selected group of widely scattered seismograph stations.

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REPORT OF RESEARCH COMMITTEE ON LAND EROSION, 1946

W. C. Lowdermilk, Chairman

Reed W. Bailey D. H. Eargle Charles R. Hursh
Carl B. Brown H. A. Einstein C. F. Stewart Sharpe
George B. Cressey W. D. Ellison Vito A. Vanoni

The undertaking of your Committee on Land Erosion involves a number of questions which have been under discussion for some time and on which recommendations are made in this report. We have the benefit of opinions of a number of AGU members actively interested in this field of inquiry.

Land erosion includes a wide range of phenomena and their results. In fact, land erosion is one of the most dynamic of geophysical processes. Erosion of land in one area and transport and deposition of erosional debris on another in time unload and overload different areas. This shift in loads on the Earth's surface brings about instabilities in the Earth's crust that set going a number of processes involving tectonophysics, faulting and crustal movements, seismic waves, volcanic eruptions, influences on climatic change, regimens of runoff, and in a remote way on ocean currents. But it is specified that the work of the Committee on Land Erosion does not overlap the work of existing Committees, such as that on Dynamics of Streams, under the able chairmanship of Laurence Straub, and that of Glaciers, under the able chairmanship of François E. Matthes. There is no intention to duplicate the work of these Committees nor to amalgamate them. There is more work to do than can be done by these three Committees altogether. It is, rather, the purpose that the Committee on Land Erosion give its chief attention to the dynamics of erosional processes in their inception and to take up those phases of erosion not hitherto covered so as to complete the picture of Earth-sculpturing processes. Collaboration, then, is sought to leave no important area between Committees uncovered. This is being worked out in conferences with Chairmen of the Committees on Dynamics of Streams and on Glaciers and with President Church.

Scope of the work of the Committee on Land Erosion falls within the general purpose of the AGU to stimulate initiative and cooperation of investigators in the dynamics of Earth sciences. Land erosion would include sculpturing processes of the Earth's surface chiefly by action of wind and water. While of lesser magnitude than processes on land surfaces, erosion of the sea floor would properly come into consideration, in collaboration with workers in oceanography. The principal interest of your Committee will center on the dynamics of processes of erosion beginning with action of raindrops and turbulent mechanisms of wind. To bring the work within limits of practical possibilities, it will be advisable to give attention to those phases and processes of land sculpturing that affect utility of the Earth's surface and resources. It is advisable at first to give special attention to those phases of land erosion that can be measured and reasonably estimated.

In carrying out such an objective, it will be needful, first, to establish as nearly as can be the "geologic norms" of erosion in a landscape and their changes in amount and rate in the course of geologic time since the Ice Age.

Such an evaluation of natural processes is useful to serve as a base to determine the second phase; namely, the degree of acceleration of such processes that may have been or are being caused by the activities of man and/or his agencies in his comparatively recent occupation of the Earth.

The third phase of the Committee's work includes an evaluation of the consequences of accelerated erosion in its physical results, in sculpturing land surfaces, in sorting, transport, and deposition of eroded material, and in its effects upon the utility of land and water resources for human society.

Carl B. Brown has emphasized the usefulness of records of sediment production from watershed areas as a measure of "geologic norms" of erosion and of comparative acceleration or reduction in rates of erosion. A large amount of quantitative data is available which has not been properly computed, analyzed, or adapted to the purpose at hand. Much of it is unpublished in any form. For example, there are hundreds of usable records covering periods of a year or more for watershed areas. These are records of suspended load measurements, reservoir surveys, valley sedimentation surveys, debris basin surveys, harbor surveys, and the like. These are cumulative records which reflect a prevalent condition in a watershed. An inventory of such data is being undertaken.

An example of this type of work is set forth in "Rates of Sediment Production in Southwestern United States," Technical Bulletin 58, of the United States Department of Agriculture. More assistance is needed to make full use of records already available.

D. H. Eargle brings some interesting information to the attention of the Committee. He has been working in the southern Atlantic and Gulf Coastal Plain, where he reports observations on different aspects of natural and man-induced erosion in areas of differing geological formation and structure and physiographic history. For example, the "Black Belt" of soft Selma Chalk differs sharply from areas on each side. "Providence Canyons" of Stewart County, Georgia, lie in materials of the same age. The differences in land forms, soils, and their erosional characteristics have been influenced by differences in lithology. Other differences have been brought about by events of physiographic history in late geological times. Covering of the land with loess in the vicinity of the Mississippi River and the fluctuations of sea level have produced terraces of the coastal plain, and the cumulative action of rivers has affected large areas of the Coastal Plain. These land forms set the stage for operation of erosional potentials in characteristic ways.

A fourth phase of the Committee's work will include studies of the manifold effects of measures for control and modification of land erosion. For example, bench terracing of land with rock walls in certain parts of the world has doubtless modified geologic norms of erosion. When maintained, terrace walls have reduced local geologic norms of erosion, and when broken down have accelerated them.

Another example will be the effects of soil conservation measures. It is not yet clear how far such measures will restore geologic norms of erosion in a given landscape. Methods of measuring long-range effects of such works are highly desirable.

Still another example: Forthcoming effects of a dam across a stream should be fully analyzed so as to forecast the general and specific effects of establishing abnormal base levels in a stream valley. Reservoirs will, in time, silt up unless special measures are taken to vent silt through the dams. Some reservoirs will silt up more rapidly than others. Above the dam and its reservoir level of water or silt, stream sculpturing will be modified by the new base level of cutting that is established by a dam. Similar effects may be expected that come about above hard rock dikes across an actively cutting stream. A forecast of these effects will be of value in possible location and design of dams to attain such effects. In short, data derived from such studies may well give rise to a new science, which may be designated as physiographic engineering.

In the long look ahead, research may well perform a prophetic function in Earth sciences. Research seeks to evaluate trends and outcomes of such trends, so as to prepare answers to questions that will come up in future, as well as solve insistent problems of the present. In working out a successful and lasting adjustment of human societies to resources of the Earth, such a science of physiographic engineering may also be useful in making the highest and fullest use of Earth materials and forces to supply essential human needs.

A long-range as well as a short-range view of the nature of investigations is called for to determine the character, extent, and importance of land erosion, as well as its modification, reduction, and control in the interests of human welfare. Such investigations and measures to be effective need to be founded on the most thorough scientific researches. Guidance, modification, and "control" of these forces will be practicably possible only when these forces are correctly evaluated under actual conditions. Specific experiments are required to isolate and measure variable forces, and comprehensive experiments are necessary to follow and evaluate effects of variables in different complexes of forces under natural conditions.

Methods of study will form an important part of the work of the Committee for collaboration. Such problems to be considered are: (1) An inventory of investigations on erosion now under way; (2) dynamics of raindrops in etching land surfaces and movement of soil down slope by rain splash; (3) methods for the determination of the rates of erosion with specific recommendations for standard methods of measurement; (4) evaluation of direct consequences of geologic norms of erosion by water and by wind on land under undisturbed and disturbed conditions; (5) evaluation of indirect consequences of erosion by the movement and deposition of sediments; (6) extent and significance of accelerated erosion as created by man and his agencies; and (7) evaluation of measures and works for reduction and "control" of erosion.

The Committee has under study plans to analyze the factors of land erosion by wind, by water in rills and gullies, by wave action, by soil creep, solifluxion, and by slides, and to survey the investigations thus far made to determine what factors have been adequately measured and what yet need to be measured. By pointing out gaps in going investigations, encouragement may be given to complete needed information on this subject. Calls for investigators to report findings are being made, and arrangements for the interchange of information on methodology, experimental procedures, and findings of investigations, at the Annual Assembly of the American Geophysical Union and through papers and discussion in the Transactions of the Union.

Your Committee is encouraging (1) the development of standards for computation and analysis of existing data, (2) Federal, State, and local agencies to make such data available in their most basic form, together with such analysis as is possible now, and (3) the development of a program to encourage interested agencies to collect and analyze additional data of this type.

Erosion of volcanic ash about the new volcano of Parícutin--It is proposed that the Committee on Land Erosion give attention to erosional phenomena in specific areas. Such a project has been called for by the National Research Council through the Chairmanship of Richard E. Fuller. Through collaboration with the Comisión Impulsora y Coordinadora de la Investigación Científica, the National Research Council is taking advantage of the unique opportunity afforded science to study the life history of a volcano from birth, so to speak. As many phases as possible of the eruption of Parícutin and its effects are being studied. Erosion in the layer of volcanic ash spread over some 400 square miles occurs in spectacular proportions, and has done more damage, it is reported, than have lava flows that nonetheless have covered several thousand acres and destroyed two villages. This study has been made a project of the Land Erosion Committee.

The Symposium of the American Geophysical Union on Land Erosion held at the Annual Assembly in Washington in 1941 serves as a beginning in the undertakings of your Committee. Another Symposium is proposed for the coming year to stimulate old investigations delayed or interrupted by the War and to encourage new undertakings in this field.

Washington, D. C.

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LETTER TO THE EDITOR

SEISMIC SURFACE-WAVE VELOCITIES OVER THE ATLANTIC OCEAN

A moderately strong earthquake was recorded at Fordham University on November 3, 1946; the arrival time of P was $19^{h}43^{m}19^{s}$, U. T. The United States Coast and Geodetic Survey issued card No. 40-46 dated November 6, 1946, giving the origin time of this shock as $19^{h}32^{m}.5$ U. T. and the provisional epicenter 0° latitude, 16° west longitude, southwest of Liberia, Africa.

The surface waves were recorded clearly enough so that Lq and Lr are easily distinguished on the records of the three-component Galitzin-Wilip seismograph. The path of these waves from epicenter to station is wholly under the Atlantic Ocean, a distance of 7370 km, calculated by the haversine relation. Atlantic shocks at such or greater distances with all ocean paths occur only at infrequent intervals, and the information on surface-wave velocities in the Atlantic is very meager [see GUTENBERG, B., and RICHTER, C. F., On seismic waves, Third Paper, Gerlands Beiträge zur Geophysik, v. 47, pp. 73-171, 1936; MACELWANE, J. B., Physics of the Earth, v. 7, Chapter 10, McGraw Hill, 1939; LYNCH, W. A., Earthquake notes, v. 17, p. 8, December 1945].

The surface-shear waves Lq and the Rayleigh waves Lr were as follows: Lq_{N}; travel time--$28^{m}.3$, velocity--4.3 km/sec, period--21 sec; Lr_{ZNE}; travel time--$30^{m}.5$, velocity--4.0, period--24. Lq was recorded better on the N-S component than on the E-W component, the azimuth being 112°. Microseisms too were much stronger on the E-W component than on the others, but they did not interfere with the recording of Lr.

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NOTES AND PERSONALIA

NOTES

Recent seismological developments in Colombia--The seismograph station of the Instituto Geofisico de los Andes Colombianos at Bogotá recently installed two new horizontal-component Sprengnether seismographs. The first earthquake was recorded on these instruments on October 18, 1946. The Institute has had a Benioff vertical in operation for several years. J. E. Ramirez, the director of the Institute, writes that a new station equipped with a vertical- and two horizontal-component Sprengnether seismographs will be installed at Chinchina, Colombia, during 1947.

Proposed study of the Gulf of Mexico--The Atlantis sailed January 2, 1947, on a cruise which will be principally devoted to an oceanographic survey of the northwestern portion of the Gulf of Mexico. Much of the geology of petroleum exploration and development involves detailed determination of past marine environments from examination of the sediments and fossil Foraminifera and remains of the hard parts of other organisms. Interpretation is based upon a comparison with similar sediments and similar organic remains being deposited in marine environments at the present time. Relatively little accurate data are available on these modern materials. The work on submarine geology which has been done and the work projected has an important bearing on petroleum exploration and development.

The largest petroleum-producing region in the United States is the region bordering the Gulf of Mexico. It appears probable that many of the younger petroleum-producing sediments were deposited under conditions similar to those now obtaining in the adjacent Gulf of Mexico. It should be emphasized, however, that this cruise is in no way concerned with petroleum exploration. It is essentially a study of modern marine environments.

Three traverses will be run from the shore out to about 2000 fathoms in the central parts of the Gulf, on which the following work will be performed. Every few miles bottom samples and long cores will be taken. It is hoped that cores up to 15 feet long may be obtained. In addition to this, serial tows will be made for plankton with self-closing nets at various depths throughout the water column. Complete hydrographic stations will be occupied frequently, at which temperatures will be taken from top to bottom, and water samples will be collected for chemical analysis. Continuous bathythermograph recordings will also be taken.

This expedition is designed to present an integrated program in which several aspects of oceanography are considered. This is essential if a well-rounded picture is to be gained of a particular region or problem. It is impossible to separate all of the marine sciences, a tendency which has been so characteristic of much of the work in the past. However, some one aspect of oceanography should be emphasized on any single expedition, and in this case, marine sedimentation will receive the chief emphasis.

Patterson Medal in Meteorology--The inauguration has been announced of the Patterson Medal to be awarded each year to a resident of Canada and Newfoundland for achievement in meteorology. The medal was founded by friends and associates of Dr. John Patterson, retiring Controller of the Meteorological Service of Canada and Honorary Professor of Meteorology of the University of Toronto.

Change in British policy regarding science in the Colonies--It has long been the policy that only such services as colonies could support from their own revenues would be available to colonies. Over the last 16 years, however, there has been a change in this policy, so that now considerable funds of the British Empire have gone to support economic development and related research. Among the outstanding results of this change have been a centralized Geodetic and Topographical Survey, a centralized Geological Survey, a comprehensive Meteorological Service, a more systematic approach to agricultural problems, comprehensive organization of medical research, and a new emphasis on the social sciences.

Plans for new vulcanological laboratory in New Zealand--The Department of Scientific and Industrial Research of the New Zealand Government plans to establish a vulcanological laboratory at Rotoria, North Island. The plan includes the installation of seismographs, geophones, and other instruments for observation of phenomena in the thermal regions.

Apia Observatory, Western Samoa--On December 8, 1945, the Apia Observatory reverted to the Department of Scientific and Industrial Research and J. W. Beagley assumed control as Director in place of Flight-Lieutenant H. B. Sapsford, who had been serving as Acting Director and who began his demobilization leave on that date. In December, Sapsford was transferred to the Department of Scientific and Industrial Research, and he returned to New Zealand early in 1946. In the future this Department will be responsible for the conduct of the geophysical activities of the Observatory. The meteorological work, however, will remain under the Royal New Zealand Air Force with Flight Officer J. H. Croxton in charge. On December 8, 1945, E. Marsden, Secretary of the Department of Scientific and Industrial Research, paid a brief visit to the Observatory.

Swedish deep-sea expedition--A deep-sea expedition under the direction of Hans Pettersson of the Oceanografiska Institut in Goteborg will sail about March 1, 1947, on a 15 months' cruise around the world, on a four-masted schooner, chiefly in the lower latitudes.

Relocation of the seismograph station of the Geological Survey of China--Y. S. Hsieh, in charge of the Division of Geophysics of the National Geological Survey of China in the absence of S. P. Lee, writes under date of November 1, 1946, that the Pehpei seismograph station at Chungking, China, suspended operations at the end of May 1946. Pehpei had been established after Chiufeng ceased operations. It is planned to rehabilitate the Geological Survey in the original compound in Nanking, and as soon as the seismographs arrive from Pehpei a new station will be set up. The address of the Survey is 942 Chukiang Road, Nanking, China.

New magazine concerning the Pacific--A new quarterly publication, Pacific Science, devoted to the biological and physical sciences of the Pacific area, is to be published by the University of Hawaii starting in January 1947. Editor-in-Chief is E. H. Bramhall.

Advisory Committee for the University of Miami Marine Laboratory--An Advisory Committee consisting of Waldo L. Schmitt, Albert E. Parr, Paul S. Galtsoff, and Daniel Merriman has recently been appointed to work with the Director, F. G. Walton Smith, to promote the development and study of tropical marine biology and oceanography in cooperation with the research programs in these fields in general.

Division of Geophysical Exploration, United States Bureau of Mines, transferred--The Division of Geophysical Exploration of the United States Bureau of Mines has been transferred to the Section of Geophysics of the United States Geological Survey, effective November 16, 1946, by the Secretary of the Interior.

New British meteorological magazine--The Council of the Royal Meteorological Society of Great Britain is publishing a new monthly magazine, Weather, with contributions by leading scientists, but written in a vein understandable to non-specialists.

Ninth Washington Conference on Theoretical Physics--The Ninth Washington Conference had as its theme "The physics of living matter," and was held under the joint auspices of George Washington University and the Carnegie Institution of Washington, October 31 to November 2, 1946.

New electrical computer at Ohio State University aids in flood routing--A newly designed and built electrical computer has demonstrated its effectiveness in the routing of flood flows through reservoirs and down channels in a recent demonstration, saving much time and effort in computation under rapidly changing flood conditions.

Civil Service examinations for Geophysicists--The Civil Service Commission announced that unassembled examinations would be held in December, 1946, for Geophysicists for grades ranging from P2 to P6. Although the closing date (January 2, 1947) is past, it is the general understanding that such examinations may be reopened upon request. The work specified related especially to Geodesy, terrestrial magnetism and electricity, seismology, and cosmic-terrestrial relationships.

PERSONALIA

H. P. Berlage of the Netherlands left the United States via the West Coast during November 1946, en route to the East Indies. He was returning to Batavia to assume the direction of the Meteorological and Geophysical Service of the Netherlands East Indies, and to reestablish the seismograph stations.

Robert C. Bundgaard has been appointed to the staff of the Military Attache, American Embassy in Norway, to engage in meteorological work.

William D. Collins, Chief of the Quality of Water Division of the United States Geological Survey, has retired after 41 years of government service. S. Kenneth Love, who has been with the Survey since 1928, has been named his successor.

A. Defant became Director of the Institut für Meteorologie und Geophysik der Universität Innsbruck (Schöpfstrasse 41, Innsbruck, Austria) in January 1946. In a letter to R. B. Montgomery he notes that all new publications are lacking in Innsbruck. He has completed the manuscript for a large "Lehrbuch der Ozeanographie," which is awaiting opportunity for publication. The Institut und Museum für Meereskunde in Berlin, of which he was formerly Director, was destroyed.

Pentti Eskola, Geological Institute, Helsinki University, Finland, visited in the United States in the autumn of 1946 as the Finnish delegate to the meetings of the National Academy of Sciences.

G. T. Faust has returned to the United States Geological Survey, Washington, D. C., from the Department of Geology, University of Indiana.

R. E. Gibson has resigned from the staff of the Geophysical Laboratory, Carnegie Institution of Washington, to accept a position as Professor of Chemistry in the Institute of Cooperative Research of the Johns Hopkins University. He will be stationed at the Applied Physics Laboratory in Silver Spring, Maryland.

J. W. Greig has returned to the Geophysical Laboratory, Carnegie Institution of Washington, following a leave of absence during which he served with the Operations Analysis Section of the 21st Bomber Command.

Benjamin G. Holzman, Deputy Chief of Air Staff for Research and Development, has been elected Chairman of the District of Columbia Branch of the American Meteorological Society.

C. B. Hunt has been appointed Regional Geologist for the United States Geological Survey, and is in charge of the Salt Lake City regional office.

A. H. Koschmann, of the United States Geological Survey, has been transferred to Denver, Colorado.

T. S. Lovering, who has been working on a project in Utah for the United States Geological Survey, has returned to the Department of Geology, University of Michigan.

Thomas J. Maher, United States Coast and Geodetic Survey, retired on September 30, 1946, after nearly 40 years of service. From 1944 to his retirement he was Supervisor of the Midwestern District at Portland, Oregon. He has also held the assignments of Supervisor of the Eastern District at New York City, Director of Coast Surveys at Manila, Inspector of the San Francisco Field Station, and Commanding Officer of a number of the Survey's ships.

H. E. McKinstry has returned to the Department of Geology at Harvard University from his war-time work with the United States Geological Survey in Washington.

O. E. Meinzer, Chief of the Division of Ground Water, Water Resources Branch of the Geological Survey, has retired. Dr. Meinzer, a graduate of Beloit College, joined the Geological Survey in 1906 and has directed its groundwater investigations since 1911. A. N. Sayre has been appointed as his successor.

Howard A. Meyerhoff, until recently the Executive Secretary of the American Association for the Advancement of Science, has left for Argentina, where he will lead an expedition of the Argentine Government into the Southern Andes on a scientific mission.

Erik Palmén, Director of the Thalassological (Oceanographic) Institute, Helsingfors, Finland, has been in the United States since July 1946, serving as Visiting Professor of Meteorology at the University of Chicago.

W. H. Parsons has left the National Bureau of Standards to join the staff of Wayne University in Detroit.

J. W. Peoples has returned to Wesleyan University, Middletown, Connecticut, from his war-time job with the United States Geological Survey in Washington.

Americo R. Peracca, of the San Francisco office of the United States Geological Survey, has been detailed to Caracas, Venezuela, for one year to act as Consulting Engineer to the Venezuelan Government on hydrologic problems of Venezuela.

John C. Reed, formerly Acting Chief Alaskan Geologist and Assistant Chief Alaskan Geologist of the United States Geological Survey, has assumed the duties of Staff Scientist, Office of the Director. He will act as a consultant and advisor to the Director, will advise and make recommendations to chiefs of Branches, and will carry on liaison with other Federal agencies and Territorial offices on affairs concerning Territories and island possessions. This change of duties for Reed is a part of the reorganization of the Alaskan Branch, which now becomes the Alaskan Section. Robert E. Fellows has been designated as geologist acting in charge of this new Section.

E. S. Shepperd has retired from the Geophysical Laboratory, Carnegie Institution of Washington.

Quentin D. Singewald has joined the staff of the United States Geological Survey, and has recently returned from a mission in Japan for the Survey.

J. T. Stark, who was a major in the Army and who served in the China-Burma-India theater, has returned to the Department of Geology, Northwestern University.

R. Maurice Tripp has resigned his position as Assistant to the President of the Geotechnical Corporation and has opened an office as a Consulting Geophysicist in Lincoln, Massachusetts.

Arvi O. Waananen and W. W. Dean of the United States Geological Survey have been detailed to southeastern Alaska, with headquarters in Juneau, to undertake a program of systematic investigation of the surface waters of the region.

Edward I. Walter, formerly with the Shell Petroleum Corporation of Houston, Texas, has been appointed Associate Professor of Mathematics at John Carroll University, Cleveland, Ohio. He will also serve as assistant director of the seismograph station of the University, where a set of three-component Sprengnether seismographs will be installed soon.

Joseph V. B. Wells has been named chief of the Surface Water Division of the United States Geological Survey. He succeeds Rudolph G. Kasel, who died June 14, 1945. Wells has served in the Survey since October 3, 1929. He has been assigned successively in New York and Pennsylvania, and since August, 1940, has been district engineer in Kentucky.

Paul C. Whitney of the United States Coast and Geodetic Survey, retired on August 31, 1946, after 44 years of service. He was Chief of the Division of Tides and Currents from 1928 to 1942, after which he assumed the duties of Supervisor of the Southeastern District at Norfolk, Virginia, which position he held at the time of his retirement. He served as President of the Section of Oceanography in the American Geophysical Union from 1942 to 1944.

C. A. Whitten, Chief, Section of Triangulation, Division of Geodesy, United States Coast and Geodetic Survey, has been designated as representative from the United States on the Committee of the International Association of Geodesy for the study of the question of the first-order geodetic triangulation of Europe.

Henry G. Avers, Chief Mathematician of the United States Coast and Geodetic Survey, died January 19, 1947, after an illness of several weeks. Mr. Avers was born at Elmore, Ohio, March 6, 1886, and received his collegiate education at Ohio Northern University and George Washington University. He became a member of the staff of the Coast and Geodetic Survey in 1908. He has been active in affairs of the American Geophysical Union, served on a number of committees, was Secretary of the Section of Geodesy, 1929 to 1931, and President of the Section from 1932 to 1935.

H. H. Clayton of Canton, Massachusetts, meteorologist and student of cosmic-terrestrial relationships, died October 27, 1946, at the age of 85 years. He was born at Murfreesboro, Tennessee, and his early adult years were spent in work at Harvard and Blue Hill observatories. From 1913 to 1922 he was Chief of the Forecast Division of the Argentine Weather Service, and subsequently devoted his life to research with the Smithsonian Institution and to private research. He had been a member of the American Geophysical Union since 1924.

Oskar T. Dauelsberg, hydraulic engineer with the United States Geological Survey at Portland, Oregon, died September 15, 1946, at the age of 40 years. He was born in Germany, and received his baccalaureate degree from Oregon Institute of Technology.

Alfred C. Gregory, Engineer of Water and Sewers of the city of Trenton, New Jersey, died suddenly on November 30, 1946, at the age of 74 years. He was born in New York City and was graduated from Rutgers University in 1896, and entered the service of the city of Trenton in 1911.

Gleason W. Kenrick, radio physicist with the Watson Laboratories, on leave from his position as Professor of Physics and Director of the Radio Research Laboratory, University of Puerto Rico, died October 29, 1946, at the age of 45 years. Dr. Kenrick was born at Brockton, Massachusetts, and did his collegiate work at Massachusetts Institute of Technology. He had been a member of the Union's Committee on Cosmic-Terrestrial Relationships since 1940.

G. F. Loughlin, geologist with the United States Geological Survey since 1912, and Chief Geologist since 1935, died October 22, 1946, at the age of 65. He was born in Hyde Park, Massachusetts, received his academic training at Massachusetts Institute of Technology and at Yale. He was an outstanding authority on metalliferous deposits.

Albert E. Staniland, Associate Professor of Mathematics at the University of Pittsburgh, died June 28, 1946, at the age of 48. Dr. Staniland took his undergraduate work at Denison and his doctorate at the University of Pittsburgh, where he remained on instructional and research work. The geometry of the complex domain was his particular field.

Fred W. Stiefel, President of the Stiefel Construction Company, New York, died in July 1946, as the result of injuries received in a motor car accident. He was born in New York, and was 54 years old. He received his academic training at Columbia University, and in his direction of many construction and mining enterprises, had contributed full measure to geophysical research, both directly and through stimulation of others.

Russell R. Waesche, Admiral in command of the Coast Guard throughout the War, died October 17, 1946, at the age of 60. He was the first commandant of the Coast Guard to be awarded the rank of full admiral. He had been in failing health since his retirement on December 31, 1945.

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of November 29, 1946

The meeting was called to order at 10^h05^m in the Reading Room of the National Academy of Sciences - National Research Council Building, 2101 Constitution Avenue, Washington, D. C., President L. H. Adams presiding.

Present--Twenty-two persons were present, namely: L. H. Adams, K. H. Beij, L. P. Disney, J. A. Duerksen, Jno. A. Fleming, R. E. Fuller, H. D. Harradon, Earl Ingerson, H. F. Johnston, David G. Knapp, W. D. Lambert, W. C. Lowdermilk, A. G. McNish, Leonard M. Murphy, Frank Neumann, Irwin Roman, W. L. Schmitt, Waldo E. Smith, W. D. Sutcliffe, C. W. Thornthwaite, R. H. Weightman, C. A. Whitten. Excused because of absence from the city or for other reasons were: J. E. Church, L. P. Hammett, M. K. Hubbert, L. L. Nettleton, F. W. Reichelderfer, V. C. Stechschulte, L. G. Straub, and W. T. Thom, Jr.

Minutes--The minutes of the meeting of the Executive Committee on October 25, 1946, were not read; it was agreed to postpone approval until a later meeting, after publication in the December Transactions.

General Secretary's Report

Inasmuch as the General Secretary presented a detailed accounting of Union activities at the meeting on October 25, 1946 [Trans., v. 27, no. 6, pp. 903-906, Dec. 1946], only a brief report was submitted.

Special Committee on Finance and Advertising in the Transactions--The Special Committee on Finance and Advertising was appointed by the President promptly after the last meeting as follows: Irwin Roman (Chairman), K. H. Beij, Jno. A. Fleming, C. A. Whitten, and R. M. Wilson.

National Roster--Word has come from the National Roster that their plan is to complete the vocational booklet on Geophysics as soon as possible; the Union, at the request of the Roster, has promised its cooperation.

American Geological Institute--The reports of the Committees appointed in October 1945, to consider affiliation of geological societies are now at hand. It was moved and approved that the membership be polled, at the same time that elections are carried on, to determine the desires of the membership with regard to adherence in principle to affiliation, which ballot, if favorable, will permit the Executive Committee to make final determination on affiliation.

Miscellaneous--The General Secretary reported that President Adams appointed C. L. Garner as the Union's representative at the Fourth General Assembly at the Pan-American Institute of Geography and History and at the Third Pan-American Consultation on Cartography held in Caracas in August 1946. He also appointed William E. Wrather representative of the Union at the Second Pan-American Congress of Mining Engineering and Geology held in Brazil in early October; and Bradford Willard as representative of the Union at the inauguration of the new President at Lehigh University on October 20, 1946.

Action on General Secretary's report--The General Secretary's report was ordered approved and filed.

Reports of Standing Committees

Nominations--Chairman Weightman presented the recommendations of the Committee for the offices of President, Vice-President, and General Secretary for the triennium July 1, 1947, to June 30, 1950. It was also reported that the present General Secretary would not accept renomination to the position he has held since 1925. The report was discussed in detail, several of those nominated and present at the meeting asked that their names be withdrawn, and suggestions were made for additional nominees. The Chairman of the Committee was instructed to secure the consent of each nominee. The following were selected as the "official nominees": For President, Walter H. Bucher and O. E. Meinzer; for Vice-President, Ernst Cloos and H. U. Sverdrup; and for General Secretary, K. Hilding Beij and John Putnam Marble.

The Executive Committee, by unanimous vote, expressed the desire that Jno. A. Fleming, General Secretary of the Union since 1925, be elected to the post of Honorary President for life, in recognition of his long and diligent service in the upbuilding of the Union; the post, bearing full voting privileges in the Executive Committee, will be especially created to honor Dr. Fleming. The Committee on Statutes and By-Laws was also instructed to determine ways and means of making such designation legal, and to proceed accordingly.

Reports of Committees on Nominations for the various Sections, in so far as available, were read; these included Geodesy, Seismology, Oceanography, and Volcanology. Reports for the other four Sections are in preparation.

Irwin Roman suggested, in case the same nominees were voted upon for President and for Vice-President, that the nominee receiving the second greatest number of votes for the Presidency be declared elected Vice-President; he suggested this for consideration in subsequent elections. No action followed discussion of this matter.

Membership--Acting Chairman Roman noted that with the list of 45 new members, now being voted upon by mail by the Executive Committee, the membership is 2888. Great satisfaction was expressed with the excellent work being done by the Committee on Membership.

Finance and Advertising--Chairman Roman made the report as given in Appendix 1, attached. The report was approved, instructions were given that the steps proposed be vigorously pursued, and, in accordance with the request of the report, the Committee was discharged with unanimous expression of thanks for its thorough consideration of its responsibilities.

Surveys and Maps--President Adams reported the resignation of Chairman Borden, because of assignment to duty at sea in the Pacific. The President will appoint Borden's successor promptly.

New Business

Foreign and Domestic Publications--It was agreed that the foreign and domestic publications used in compiling bibliographies should be distributed to organizations where they will be useful. The Library of Congress (where there is great need of complete files of geophysical references as evidenced by many requests for information pertaining to both national and international information, is to be given first opportunity to accept these. Any remaining will be offered to the Smithsonian Institution and interested special research bodies.

Consent of nominees--It was agreed that in the preparation of ballots for elections of officers, the respective Union and Section Committees on Nominations should obtain the consent of the nominees.

Future of the Union--The General Secretary emphasized the importance of considering means of improving the financial status of the Union after the expiration of the grant of the Rockefeller Foundation on June 30, 1947. The goal of 4000 membership set has not yet been attained, largely by reason of the emergency conditions of the War. Without doubt the drive for Corporation Members and for advertising, as per the excellent report of the Special Committee on Finance and Advertising, will aid, as will also the increasing sales of the Transactions. Each member of the Executive Committee should take this subject under advisement for constructive suggestions to insure full advantage of the Union's large potentialities in the future of geophysics. Attention was directed especially to the early plan to circularize for membership suitably qualified persons selected from published lists of members of organizations having any geophysical interests or contacts--a plan not yet followed in detail but which should be put in operation at once. Members on the Inactive List should also be contacted and solicited to resume membership. The office will welcome and follow through suggestions submitted for elections of new members. In making these remarks the General Secretary stressed that the development of additional resources and members was a necessary responsibility of the Union for the attainment of its objectives and the advance of geophysics in an even greater degree than the past history of the Union has so well recorded.

It was agreed that the President and the General and Executive Secretaries should prepare, sign, and forward to all the members of the Executive Committee, a letter summing up the situation and the needs. A general letter based upon replies could then be prepared for the entire membership as to the opportunities of even greater progress than that attained so successfully thus far.

Adjournment--There being no further business the meeting adjourned at 13^h20^m.

JNO. A. FLEMING
General Secretary

WALDO E. SMITH
Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON FINANCE AND ADVERTISING IN THE TRANSACTIONS

Irwin Roman, Chairman

K. H. Beij | C. A. Whitten
Jno. A. Fleming | R. M. Wilson

After considering various problems, the Committee decided to recommend the following proposals to the Executive Committee for approval:

1. List corporation members on one or more pages immediately after the final page of text in each issue of the Transactions.

2. Include in the Membership Directory a list of corporation members as a distinct unit.

3. For the present, accept no advertising in the Transactions other than display cards for educational institutions and for professional individuals or groups.

4. Corporation membership listing shall be on the basis of not more than eight entries per page, space for each entry to have full-page width. Each entry shall show the name, activity, and address of the member.

5. Educational institutions may purchase space for cards in an appropriate listing, on the basis of not more than ten spaces per page, each space to be a half-page in width. Each card shall show the name of the institution, special fields of geophysical interests, and address.

6. Professional cards shall be available to individuals or groups, to members and non-members alike, on the basis of not more than ten cards per page, each card to be a half-page in width. Each card shall show the name, fields of geophysical activity, and address of the advertiser.

7. Acceptance of copy for educational and professional cards shall be the responsibility of the Editorial and Publication Committee of the Transactions.

8. The following rates are recommended: (a) For corporation membership listing, no charge beyond the established annual membership dues of $100; and (b) for educational or professional cards, $10.00 per issue or $50.00 for six consecutive issues.

9. Each institution, individual, or group purchasing cards as described under Items 5 and 6 shall receive one copy of each issue in which the card appears.

10. The Committee on Membership shall assist the Executive Secretary in the solicitation of institutions, individuals, and groups for the insertion in the Transactions of educational and professional cards.

With your acceptance of this report, your Committee considers its assignment completed and requests that it be discharged.

SECTION ACTIVITIES

SECTION OF HYDROLOGY

President's Greetings, Annual Meeting of 1946

Although this is a year of relaxation after the stress of war, steady progress can be reported.

Administration--Our Vice-President Straub and Secretary Beij are back once more in full activity, released from their war services. Vice-President Straub would be present except for the railway strike. Happily I had been persuaded to fly, but even so was grounded for several hours at Cheyenne.

The duties of administration have now been shared more fully with the Secretary. The President still serves as administrative director but the development of the annual program, relinquished by Chairman Hertzler, has been assigned to the Secretary. The acceptance of papers for publication has already been transferred to a Board of Editors directed by the Union. The Co-editors of our Section are Walter B. Langbein and Walter T. Wilson. The legislative branch of the Section is still the Executive Committee, but it has been broadened by the addition of past officers of the Section, the chairmen of all committees, and the two Section editors, whose vote is advisory only but no less potent.

Chairman Hertzler, who has for a time been diverted to other fields, will still retain his place on the Committee. L. K. Wenzel, who has been passing through a prolonged period of convalescence, is expected to be with us again this year. Stanley W. Lohman has been chosen by the Executive Committee to fill the place left vacant by the death of Robert E. Horton.

Regional meetings--The spirit of regional meetings is strong, but their expansion is slow. The present year the South Pacific Area met at Sacramento under the direction of Chairman Veihmeyer. Next year it will meet at Pasadena as a guest of the California Institute of Technology. The North Pacific in cooperation with the North Continental Divide Area planned earnestly to meet at Vancouver, British Columbia, or at Portland, Oregon, but there was no room at the inns. John C. Stevens, recent President of the American Society of Civil Engineers and Chairman of the North Pacific Area, is already planning for the coming year. The spontaneous dinner meeting, organized at Washington, D. C., last winter under the direction of D. B. Krimgold, has become an established event. It was organized by the hydrologists but is for others also.

The central meeting on ground water at the University of Illinois, which was cancelled because of the War, has not been held as yet. The University of Iowa, quite independently, has now held its third conference in hydraulics. It could become the center for a regional area in the Mississippi Valley. The Southeast Regional Area, centering around Atlanta and Knoxville, will probably now be directed by Albert S. Fry of the TVA. A cooperative effort of Sections of the Union in New England is being planned by Richard M. Field and Harlan T. Stetson. The eastern field of regional meetings is apparently being summer-fallowed for a later harvest. At the urging of Chairman Sherman the direction of the work has been centered in the President.

Research Committees--The broad Committee on Erosion, under the chairmanship of W. C. Lowdermilk, has had a rich year of observation afforded by the new volcano Parícutin in Mexico.

The Subcommittee on Permeability of the Committee on Ground Water seeks the status of a Special Committee in order to enlist the cooperation of organizations other than the Section of Hydrology. C. E. Jacob, who is acting for L. K. Wenzel, has already gathered a personnel of 14.

F. J. Veihmeyer of the University of California at Davis, who has a long tradition of research in irrigation, has relinquished the chairmanship of the Committee on the Physics of Soil Moisture to L. A. Richards of the United States Regional Salinity Laboratory at Riverside, California, but will continue to share in the work.

The Committee on Lakes, directed during War years by S. T. Harding of the University of California, and long devoted to desert lakes, will now emphasize the thermal characteristics of fresh-water lakes under the chairmanship of Phil E. Church of the University of Washington, who has accumulated much material on Lake Michigan.

The reports of the Committee on Snow will be prepared hereafter by Richard C. Farrow, Vice-Chairman, who has now returned from four years of military service in Europe and will probably assume the chairmanship. The old Chairman, through multiplicity of duties, has become far too slow. It is earnestly hoped that the report will still remain a "year book" in character.

Intersociety relations--The Committee on Intersociety Relations has now been fully established. All organizations selected by the Executive Committee have accepted. The list is impressive for its breadth. Organizations and representatives are as follows: Wesley W. Horner, Chairman; American Geophysical Union, Section of Hydrology, W. G. Hoyt; American Society of Agricultural Engineers, C. E. Ramser (East), F. J. Veihmeyer (West); American Society of Civil Engineers, Wesley W. Horner; American Meteorological Society, C. F. Brooks; American Water Works Association, Samuel B. Morris; Geological Society of America, Henry R. Aldrich; Society of American Foresters, H. G. Wilm; Society of Economic Geologists, Stanley W. Lohman; Soil Science Society of America, O. R. Neal.

W. W. Horner, newly-chosen President of the American Society of Civil Engineers, has consented to accept election to the chairmanship. I should like to quote from his letter.

"I have your letter of the 15th, and will be very glad to conform to your suggestion. I am writing to W. G. Hoyt asking that he act as Vice-Chairman of the Committee on Intersociety Relations in connection with the Annual Meeting, May 27 to 29, at which I cannot be present.

"I am also asking him if he will not convene the members of the Committee, get some preliminary discussion of a desirable program, and ask the members present either to confirm him as Vice-Chairman or to designate another member in the event he is unable to serve thereafter."

The Horton Reference Library--Robert E. Horton has shown his confidence in the Section of Hydrology by leaving the bulk of his estate to aid in the publication of worthy papers. He also left his large collection of manuscripts, references, and memoranda to the Section as a reference source for engineer specialists and students. The collection has now been transferred to the office of the Union for disposal and has been catalogued by the Executive Secretary.

There may be here the foundation of a reference library in more commodious quarters, which can be visualized with the enlargement of the building of the National Research Council. It could be placed under the supervision of the Co-editors.

Honors--Citations of excellence will henceforth be awarded worthy first papers and senior papers. Recommendations may be made by the Executive Committee and Supplementary Council, but final choice rests with the Executive Committee itself. No choice was made the present year.

Election of officers--The Union has been slowly moving from Washington to the members. Papers can now be published without being presented at an Annual Meeting, and papers sent in absentia to a Meeting will be presented and discussed. The bimonthly Transactions hold the members together. Papers published in the Transactions are open for discussion, and members are urged to send their discussions to the office of the Union.

Following the last Annual Meeting, the Executive Committee of the Union recommended that hereafter all officers be elected by mail ballot of the entire membership. This has become a part of the Constitution. The several Sections will elect their individual officers. Should the Executive Committee of our Section, numbering seven in addition to the officers, also be elected?

The world--Our international kinship grew into conviction at the final session of 1944, when Peter W. Rainier related his adventure in providing water to Montgomery for his pursuit of Rommel across the African desert. That kinship has now been tinged with sorrow at the news that Rainier has perished in a hotel fire in western Canada.

The Soviet Academy of Sciences, within a month of the surrender of Germany, invited scientists from most of the countries of the world to attend its 220th Anniversary. All were guests of the Academy. Some of us flew around the world.

Iran was seen to be a snow-fed country with underground conduits for its water. India and China are in the forefront of the world in the impounding of large streams.

Norway, which planned to receive the International Union of Geodesy and Geophysics in 1942, has made plans to welcome it to Oslo in 1948.

A store of Transactions and reprints of regional meetings has long been preserved awaiting the close of the War. A list of their contents will soon be sent to various countries so that they can report their needs and desires.

Our view ahead--The coming year will be one of awakening and readjustment to peace. The young men are already active and increasing in numbers. Opportunities in our Section are wide. There is the open forum with discussion safeguards and a broad and sympathetic understanding of related fields. The mail ballot has placed the direction of the Union and the Sections in the hands of the membership. In this coming year, the leaders must be selected for the three-year period ahead. It should become a time of achievement.

J. E. CHURCH

REPORT ON ACTIVITIES OF WASHINGTON GROUP, SECTION OF HYDROLOGY AMERICAN GEOPHYSICAL UNION, NOVEMBER 29, 1945 TO DECEMBER 3, 1946

Formation of Washington Group--Approval by the Executive Committee of the Section of Hydrology of the formation of a Washington Group was announced at the first meeting on Novetmber 29, 1945. A Nominating Committee to submit nominations for offices was appointed, consisting of D. B. Krimgold, C. W. Thornthwaite, O. E. Meinzer, and E. N. Munns.

Election of officers--At the second meeting on February 18, 1946, the following officers were elected: D. B. Krimgold, Chairman; Carl F. Izzard, Vice-Chairman; and Bernard Frank, Secretary.

Summary of Meetings--Four meetings have been held since the organization of the Group: On November 29, 1945, N. H. Darton and Franklin F. Snyder spoke, the former on the early work of the Water Resources Branch of the Geological Survey, and the latter on the forecasting of river stages of the Rhine during the War; on February 18, 1946, Merrill Bernard addressed the Group on the subject "Achievements in Soviet Hydrology;" on June 17, 1946, W. C. Lowdermilk spoke on the Jordan Valley Authority; and on December 3, 1946, H. Wexler talked on the use of radar in storm detection. Attendance at the above meetings was, respectively: 70, 80, 46, and 37. Minutes of the first three meetings appear, respectively, in the February [p. 149], April [p. 305], and August [p. 618] issues of the Transactions of 1946. The minutes of the fourth meeting are below.

Advisory Group--At the invitation of Chairman Krimgold, a special meeting was held at the Cosmos Club on April 5, 1946, to discuss proposed Rules of Procedure for the Washington Group. In addition to the Group officers, those who attended were O. E. Meinzer, R. W. Davenport, and R. K. Linsley, Jr. Discussion of the Rules of Procedure suggested by Beij and Izzard and subsequent procedure led to the adoption of the rules shown at the end of this report. These were read at the meeting of December 3 and submitted to the Secretary of the Section of Hydrology for transmittal to the Executive Committee.

Minutes of the Fourth Meeting of the Washington Group--Thirty-seven members and guests heard H. Wexler, Chief, Special Services Division, United States Weather Bureau, on the subject "Radar in Storm Detection." This illustrated talk was held on December 3, at $13^{h}00^{m}$, at the National Museum Auditorium. Wexler was asked to prepare a short paper on his talk, which appears as an abstract on page 70, this issue of the Transactions.

At this meeting the Chairman announced the appointment of a Nominating Committee for next year's Group officers, consisting of O. E. Meinzer and K. H. Beij, with a third member to be selected by them. This Committee is to report at the next scheduled meeting of the Group, at which time elections will be held. Members of the Washington Group are requested to send their suggestions to O. E. Meinzer, 2923 South Dakota Ave., N. E., Washington 18, or K. H. Beij, National Bureau of Standards, Hydraulic Laboratory, Washington 25.

The meeting adjourned at $14^{h}15^{m}$.

Rules of Procedure, Washington Group, Section of Hydrology

Section 1--The Washington Group shall consist of members of the American Geophysical Union affiliated with the Section of Hydrology residing in the Washington area, and of other members of the American Geophysical Union interested in current developments in hydrology and related fields, and interested in maintaining personal contacts with fellow members.

Section 2--Officers shall consist of a Chairman, Vice-Chairman, and Secretary-Treasurer elected at the first meeting of each calendar year. These officers will constitute the Executive Committee of the Group. Its function will be to accomplish the purposes of the Group through periodic meetings, luncheons, lectures, and other appropriate means.

Section 3--There shall be no dues. Expenses shall be met by appropriate assessment at each meeting or function. The Secretary-Treasurer shall make a financial report at each meeting.

Section 4--A brief resumé of the procedure of each meeting will be sent to the President, Vice President, and Secretary of the Section of Hydrology and will be submitted to the Executive Secretary of the Union for publication in the Transactions.

Section 5--Meetings will be called by the Executive Committee of the Group.

BERNARD FRANK, Secretary

SPECIAL ANNOUNCEMENTS

Notice regarding elections--Late in February, at about the time this issue of the Transactions is released, a ballot will be sent to each member in good standing, covering election of Union and Section officers for the triennium beginning July 1, 1947, an amendment to the Statutes, and the matter of affiliation with the American Geological Institute [see this issue, page 144]. Please give this ballot your early attention, and return it promptly to the Office of AGU. Voting closes March 31, 1947.

Union Office moved to 1530 P Street, N. W., Washington 5, D. C.--The Office of the Union was moved late in January from the Department of Terrestrial Magnetism of the Carnegie Institution of Washington at 5241 Broad Branch Road, N. W., Washington 15, D. C. (where it has enjoyed the privilege of office facilities since 1925) to the Administration Building of the Carnegie Institution of Washington at 1530 P Street, N. W., Washington 5, D. C. Please address all communications for the Union to the latter address.

Twenty-Eighth Annual Meeting--The Twenty-Eighth Annual Meeting of the American Geophysical Union will be held in the National Museum and nearby meeting rooms in Washington, D. C. Monday, April 28 to Wednesday, April 30, 1947 (about a month earlier than last year), as noted in the December 1946 issue of the Transactions, page 925. Plans are progressing, though at the time of going to press (late January), the definite schedule had not been set.

This is the last call for papers for this meeting, and persons planning to prepare papers should see that titles and abstracts are in the office of the Union or in the hands of the Section Secretary [see below] by March 15, 1947. Papers will be accepted for presentation on the program in the order that word is received concerning them, and the number of papers will be limited by the available time. Complete manuscripts for consideration for publication should be forwarded in triplicate by early April if possible. Papers will be given consideration for publication in the Transactions approximately in the order received and though no definite deadline is set for papers for publication, it greatly facilitates the handling of newspaper and radio requests if copies are in hand well before the meeting date.

In connection with presentation of papers, authors must advise what if any projection equipment is necessary. This information should be sent in with the title, or, if it is not possible to do so at that time, directly to the office of the Union by April 1. Authors should consult Secretaries of Sections for time allotment for their presentations. Most papers are allowed ten to 20 minutes. When papers are written in collaboration, the authors should indicate who will make the presentation. Arrangements can be made for presentation or for reading by title of papers by authors who will be unable to be present. Unless the author indicates otherwise at the time the title and abstract are submitted, it is assumed that AGU will have first opportunity for publication of the paper. Papers for presentation only, and papers to receive consideration for publication only, are both welcome also, but the author should indicate his desires in these cases. All papers for publication will be referred to the Editorial and Publication Committee for consideration for the Transactions.

Authors should bear in mind that papers prepared for publication are not necessarily in good form for presentation (and vice versa). In oral presentation, complicated mathematical developments are usually undesirable, and references to earlier parts of the paper should be as few as possible. "Suggestions to Authors" for papers for publication were printed in the Transactions of August 1945 [v. 26, pp. 179-182] with a modification in April 1946 [v. 27, p. 306]. Reprints of the suggestions are available on request.

Our first postwar meeting last year was a very good one, with over 700 in attendance. This year, with the label "top secret" off of many items, the program should again prove to be outstanding, and early outlook for excellent attendance is good.

A number of smaller meeting rooms will be available for special committee meetings and symposia with limited attendance. Persons planning such meetings should notify the office of the Union by March 15 to make sure of room assignments and appearance on the printed program.

There will be an evening meeting and reception, with an address by the retiring President, tentatively scheduled for Monday, April 28; a smoker, tentatively planned for Tuesday, April 29; and a General Assembly, one of the features of which will be an address by Professor J. Tuzo Wilson on his geophysical research work in Canada. Announcement will also be made of the outcome of the elections, and the new officers elected for the term beginning July 1, 1947, will be introduced.

Each Section is planning at least one session; Oceanography is planning two sessions, chiefly on the theme of the oceanographic work in connection with Operations Crossroads; the Section of Terrestrial Magnetism and Electricity is also planning two sessions; Meteorology is planning two or more sessions; and Hydrology is planning four sessions. In connection with problems and plans relating to the meeting, get into touch with the appropriate Section Officers listed below, or with the office of the Union.

Geodesy

W. D. Sutcliffe, President
(U. S. Coast and Geodetic Survey
Washington 25, D. C.)

J. A. Duerksen, Secretary
(U. S. Coast and Geodetic Survey
Washington 25, D. C.)

Seismology

V. C. Stechschulte, President
(Xavier University
Cincinnati, Ohio)

L. M. Murphy, Secretary
(U. S. Coast and Geodetic Survey
Washington 25, D. C.)

Meteorology

F. W. Reichelderfer, President
(U. S. Weather Bureau
Washington 25, D. C.)

H. D. Harradon, Secretary
(5241 Broad Branch Road, N. W.
Washington 15, D. C.)

Terrestrial Magnetism and Electricity

H. Freeborn Johnston, President
(6503 Ridgewood Ave.
Chevy Chase 15, Maryland)

D. G. Knapp, Secretary
(3827 W Street, S. E.
Washington 20, D. C.)

Oceanography

H. U. Sverdrup, President
(Scripps Institute of Oceanography
La Jolla, California)

L. P. Disney, Secretary
(U. S. Coast and Geodetic Survey
Washington 25, D. C.)

Volcanology

Richard E. Fuller, President
(University of Washington
Seattle, Washington)

Francis G. Wells, Secretary
(U. S. Geological Survey
Washington 25, D. C.)

Hydrology

J. E. Church, President
(Nevada Agricultural Experiment Station
Reno, Nevada)

K. H. Beij, Secretary
(National Bureau of Standards
Washington 25, D. C.)

Tectonophysics

Ernst Cloos, President
(Johns Hopkins University
Baltimore, Maryland)

M. King Hubbert, Secretary
(Shell Oil Company
Houston 2, Texas)

American Geophysical Union
1530 P Street, N. W.
Washington 5, D. C.

TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

Volume 28 APRIL 1947 Number 2

DEFLECTIONS OF THE VERTICAL FROM GRAVITY ANOMALIES

Walter D. Lambert

With the increasing number of surveys based on astronomical coordinates and with loran stations established on oceanic islands far from the mainland and its geodetic control, there has been an increasing interest in deflections of the vertical.

Some of those who have a professional interest in deflections of the vertical but who have not analyzed the underlying conceptions seem to have the vague idea that there is something in nature that might properly be called the deflection of the vertical. In the present state of geodesy there is nothing that may properly be called the deflection of the vertical at a given point. All existing numerical values of the deflection depend on the assumed geodetic datum, and the geodetic datum might conceivably be anything whatever, though in practice the choice is confined within rather narrow limits.

The usual geodetic datum is essentially arbitrary. Two geodesists with the same general background and the same mass of geodetic material before them might hit upon approximately the same choice of a datum and then again they might not. And since the choice of a datum is arbitrary, the deflections, dependent as they are on the datum, are arbitrary also.

We diminish the arbitrariness of choice and, what is more important, we get an intrinsically better geodetic datum, if we require that the center of the ellipsoid of reference shall coincide with the center of gravity of the Earth and that the axis of the ellipsoid shall coincide with the axis of rotation of the Earth.

As a matter of fact, our United States Datum, the predecessor of the North American Datum, was not adopted as the result of any special study. At first it just grew. Geodetic positions based on a supposedly temporary datum used in the eastern part of the country were found to agree satisfactorily with the astronomical positions further west, so the geodetic positions based on the eastern datum were accepted and the United States Datum was redefined in terms of a geodetic station in Kansas. Indeed, two of the items mentioned above were not explicitly considered when the decision was made; the position of the center of the ellipsoid of reference, and the direction of its axis. These are undetermined to this day. It is precisely these two items that will be emphasized in this paper.

The word "ellipsoid" is used throughout this note in the sense of an ellipsoid of revolution. The more general term "spheroid" is avoided. It is not difficult to adapt the formula for theoretical gravity to a predetermined spheroid that is not an exact ellipsoid of revolution, but the computation of triangulation on anything except an ellipsoid of revolution requires intricate numerical calculations; whereas this note implies throughout a comparison between astronomico-geodetic deflections and gravimetric deflections. Hence, for convenience, we are obliged to stick to the ellipsoid and base our gravity anomalies on an appropriate formula for theoretical gravity.

About 100 years ago STOKES [see "References" at end of paper, 1883] did some pioneer theoretical work that may eventually enable us to refer our geodetic measurements to an ellipsoid thus ideally situated; its center at the center of gravity of the Earth and its axis coincident with the Earth's axis of rotation. If we insist that our geodetic datum shall be based on an ideally-situated ellipsoid of this sort, the only elements of our datum left undetermined are the size and shape of the ellipsoid. If we specify these, then everything is determinate and we may properly speak of the deflection of the vertical at a given point. The problem then becomes one of computation.

Stokes' mathematical developments in their original form do not give the deflections directly. The formula that he gave enables us to express the elevation of the geoid at a given point above the ellipsoid of reference in terms of the gravity anomalies. A gravity anomaly and a deflection may seem rather different in kind, but the gravity anomaly is an anomaly in the vertical component of the gravitational attraction; a deflection is an anomaly in the horizontal component. The nature of the force of which both are manifestations and the ingenuity of the mathematician make the connection between them. The ellipsoid is the particular ellipsoid already referred to, properly centered and properly oriented. The formula for the elevation of the geoid above this ellipsoid looks complicated, not to say perverse. No term of it has any obvious physical meaning. Stokes would probably have said that he was summing a series of spherical harmonics by an ingenious device. The more modern mathematician might say that he was solving an integral equation [IDELSON, 1933].

In practical application we need a contour map of gravity anomalies. From it we can deduce the elevation of the geoid at various points. From enough such elevations we could draw contour lines of the geoid elevations referred to our chosen ellipsoid. These would be height contours, exactly similar to ordinary topographic contours. If we have enough such height contours, we can estimate the slope from the distance between neighboring contour lines. The slope of the geoid is simply another term for the deflection of the vertical in a direction perpendicular to the contours. Stokes himself suggested this.

An analytic process at once more elegant and more accurate was developed by VENING MEINESZ [1928] and DE GRAAFF HUNTER [1935]. We need, as before, a contour map of gravity anomalies. The formula looks complicated, as before, but this time the leading term, the important term when we are dealing with areas near the deflection station, is of the same form as the expression used in computing topographic deflections or in the isostatic reduction of deflections of the vertical. There is a simple reason for this, which need not be discussed here. The regions near the deflection station are highly important in computing deflections, the remoter regions much less so. In computing geoid elevations the remoter regions are relatively more important. This may help to explain why we have more computations of the deflection than of geoid elevations. Because of the lack of well-distributed gravity data we have only a few computations of either kind.

It is interesting to consider how we might use gravity data to improve current processes for the computation of ordinary geodetic triangulation. If we knew the elevations of the geoid above the ellipsoid of reference, we could reduce the lengths of our measured bases to the level of that ellipsoid. At present, for lack of adequate information, they are reduced to the level of the geoid, which, for the various bases, has various positions with respect to the ellipsoid. Again, if we knew the deflections of the vertical, we could apply the proper corrections to our observed horizontal directions. These corrections may be quite appreciable, especially for inclined lines of sight at stations where the deflection is large, but for the present these corrections are almost universally ignored because the necessary data are lacking. A possible use of the deflections of the vertical determined from gravity anomalies to improve the adopted semi-axes of the spheroid of reference will be mentioned later in connection with the work of KASANSKY [1935].

Let us briefly review recent work on geoid elevations and deflections of the vertical based on actual gravity anomalies.

For the geoid elevation we have the pioneer work of HIRVONEN [1934]; it necessarily involved much guessing at gravity anomalies in unexplored areas, but the results are interesting. Hirvonen's work predicted a rather surprising rise of the geoid in the Malay Peninsula, a rise later confirmed by observation. Hirvonen's work would seem to show that for India the proper ideal ellipsoid of reference should lie some 60 meters [GULATEE, 1940, p. 116] below the geoid at the origin of the datum in order that the center of the ellipsoid may coincide with the center of the Earth. The not-so-ideal ellipsoids commonly used by geodesists keep fairly close to the geoid in the particular area under consideration, only to depart all the more widely from the geoid in remoter areas.

Work on deflections of the vertical from gravity anomalies has been done by Vening Meinesz in the Netherlands, by the Survey of India [GULATEE, 1940, pp. 97-101], and by Kasansky, in Russia. Of the work of Vening Meinesz we have few details. He makes the general statement that deflections were computed from gravity anomalies for three stations in the Netherlands and that the results agreed satisfactorily with those obtained from astronomico-geodetic work. The Survey of India also finds good agreement in a few test cases.

The work of Kasansky was more extensive than either of the foregoing and deserves careful study, not only for the results obtained but also for the methods employed. The region studied is near Moscow and covers an area of about three degrees in latitude and four degrees in longitude. This area contained a number of gravity stations so that the gravity contours could be drawn with fair accuracy; it also contained for comparison a considerable number of astronomical stations. Kasansky's astronomico-geodetic deflections and his gravimetric deflections are on two different bases, the first on an arbitrary system, the second on an ideal system, but the relative deflections may be compared and errors estimated. Let δ_a and δ_g denote, respectively, the astronomico-geodetic deflection and the gravimetric deflection (note that the subscript g is for gravimetric, not geodetic), either in the meridian or the prime vertical, for the average results to be quoted include both, and form the difference $\delta_a - \delta_g$. The mean error of this difference was found by Kasansky to be about 1″.0 (Kasansky used mean errors throughout; to find "probable" errors apply the factor 2/3). After allowing for the error of δ_a, then the mean error of δ_g, the gravimetric deflection by itself, comes out to be 0″.8. This arises from the errors of the observational data and of the contour lines based on them and on the inadequacy or absence of data for regions distant from Moscow.

Kasansky tests several groups of astronomico-geodetic stations. In one group the deflections were based on an origin at Pulkowa Observatory, about 400 miles northwest of Moscow; this was the origin of Struve's survey, one of the early Russian geodetic surveys. Bessel's ellipsoid was used; this is known to have its radial dimensions some 700 meters smaller than the ellipsoid best adapted to Russia. This error in radius was manifest in the astronomico-geodetic deflections δ_a, which changed systematically from northwest to southeast, even within the comparatively small area studied. The gravimetric deflections, on the other hand, are practically unaffected by the error in the dimensions of the ellipsoid. The error of the conventional astronomico-geodetic deflection in latitude for the center of the Moscow region is thus built up to about 2″.5.

The method of gravimetric deflections can be applied anywhere in the world, provided the gravity observations are available. We could determine from gravity observations a proper datum for South America and it would be on the same basis as a datum similarly determined for North America, even before those two continents are connected by triangulation. Gravimetric data could also be used to great advantage in the proposed readjustment of the triangulation of Europe. As mentioned in a preceding paragraph, the bases could be reduced to the ellipsoid, the observed directions could be corrected for deflection and perhaps the dimensions of the adopted ellipsoid could be improved.

The Section of Gravity and Astronomy of the United States Coast and Geodetic Survey has undertaken the determination of the elevations of the geoid and the deflections of the vertical in Missouri. For Missouri itself the work will be based on a gravimetric map of the state published by the State Geological Survey. The gravity determinations were made with gravimeters and tied in with pendulum determinations of the Coast and Geodetic Survey.

The map gives contours for the Bouguer anomaly. It was necessary to redraw the map entirely in order to have contours for the free-air anomaly. It has been assumed that, in spite of the mildly rugged topography in the Ozark area, the results from the uncorrected free-air anomalies will be reasonably satisfactory. The question of the best method of reducing to sea level, whether by an isostatic reduction, by condensation, by inversion, or by no reduction at all except the free-air reduction for elevation, has not yet been settled to the entire satisfaction of all geodesists and is too large a question to be discussed here.

This study was undertaken partly for the information that it is expected to yield, partly for the training it will afford. For instance, it will be interesting to see what we find for the position of the ellipsoid with respect to the geoid in the area of our experimental work, namely Missouri. Hirvonen's results for the United States are rather curious, differing rather markedly from accepted ideas. His results are, of course, subject to substantial modification when additional gravity data are taken into account. At the end of the job we of the Section of Gravity and Astronomy should be familiar with the various necessary techniques of what seems to be the coming method of determining deflections of the vertical, deflections less arbitrary and more scientific than those in use hitherto, deflections that may be computed even for points isolated from existing blocks of geodetic triangulation.

We shall have also a scientific basis for the choice of a geodetic datum, a datum as free as possible from arbitrary elements. The center of our ellipsoid of reference will be where it should be; the direction of the axis of the ellipsoid will be what it should be. Only the linear dimensions will be open to choice, and a comparison of the gravimetric deflections at various points with the corresponding astronomico-geodetic deflections will give us a good hold on the proper dimensions to choose. This is as near as we can come to the deflection of the vertical at a point.

As a by-product of the study we shall have a rather full and accurate table of two of the functions needed in computing gravimetric deflections. If we define Stokes' function $f(\psi)$ by the formula

$$f(\psi) = [\csc \psi/2 + 1 - 6 \sin \psi/2 - 5 \cos \psi - 3 \cos \psi \log_e(\sin \psi/2 + \sin^2 \psi/2)]/2 \; . \; . \; . \; . \quad (1)$$

we need for computing deflections a table of the values of

$$[df(\psi)/d\psi] \sin\psi = [(-\cos^2\psi/2)/(\sin\psi/2) - 3\sin\psi\cos\psi/2 + 5\sin^2\psi$$
$$+ 3\sin^2\psi \log_e (\sin\psi/2 + \sin^2\psi/2) - 3(\cos\psi\cos^2\psi/2)(1 + 2\sin\psi/2)/(1 + \sin\psi/2)]/2 \quad . (2)$$

It is also convenient to have a table of the function $\int_\alpha^\psi [df(\psi)/d\psi] \sin\psi d\psi$. The integration can not be performed in terms of the elementary functions, so it was necessary to resort to expansion in power series and to mechanical quadrature. The function $[df(\psi)/d\psi] \sin\psi$ and its integral $\int_\alpha^\psi [df(\psi)/d\psi] \sin\psi d\psi$ were tabulated at rather close intervals for the convenience of future investigators as well as of ourselves.

It will be fairly easy to interpolate in these tables in order to form special tables for whatever arrangement of zones may be deemed convenient for map reading and computation. The value of the lower limit α was arbitrarily taken as 0.01, since a zero value would have given rise to a logarithmic infinity. The tables will be published shortly.

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GRAVIMETER TIES BETWEEN GRAVITY BASE STATIONS IN WASHINGTON, D. C.

Sigmund Hammer

Abstract--Relative gravity observations in the United States and international gravity ties have been referred to several base stations in Washington, D. C. Correlation of these data has been based on gravity differences between the base stations determined by pendulum observations, some of which date back to 1893. The results of recent gravitational ties between the principal gravity base stations in Washington, D. C., using a modern high-precision gravimeter are reported and discussed. The gravimeter results indicate that the previous pendulum connections between the base stations in Washington contain errors of about 2 mg.

Introduction--Relative gravity observations in the United States, principally pendulum work by the United States Coast and Geodetic Survey, have been referred from time to time to several fundamental base stations in Washington, D. C. Furthermore, modern international gravity ties have been made into two different points in Washington. To avoid loss of accuracy in correlating all these various data it is highly desirable to have these basic points tied together gravitationally with high precision.

Previous gravitational ties between these base stations in Washington were made by pendulum observations, some of them as long ago as 1893. Also, the pendulum connection between the two base stations in Washington, which have been used in international gravity ties, was not direct. For these reasons, and in connection with other work then in progress, C. H. Swick of the United States Coast and Geodetic Survey, in 1937, requested the Gulf Research and Development Company to tie some of these base stations together with the Gulf gravimeter. This was done and the results were considered satisfactory [see "References" at end of paper, HAMMER, 1938]. However, subsequent critical re-examination of all available data in the preparation of what was planned to be the present paper showed that a pertinent, earlier (1936) Gulf gravimeter tie was quite unsatisfactory. The questionable tie was between Heyl and Cook's absolute gravity station in the National Bureau of Standards and the present gravity base in the building of the United States Department of Commerce. The uncertainty involved the sign of the correction for the relative magnetic effect of the two buildings on the readings of the gravimeter, then magnetically unshielded, amounting to a possible error of about 1 1/2 mg in the gravimeter tie between the two stations. The uncertainty in the data was confounded by the fact that the gravimeter tie, with the magnetic correction applied with the apparently wrong sign, agreed almost perfectly with a very careful pendulum tie between the two stations in 1933 by BROWN [1936]. Therefore, it was felt that publication of the results should be deferred until the gravimeter data could be checked.

The first opportunity to repeat these gravimeter ties with a magnetically shielded Gulf gravimeter [WYCKOFF, 1941] was delayed many years until the spring of 1946. The present paper reports the results of these later gravimeter ties between the three principal gravity base stations in Washington.

Description of observation points--The points observed with the gravimeter were carefully selected to be as near the pertinent pendulum base station as practicable. Detailed descriptions of the sites observed with the gravimeter follow:

Station 1 was located on the concrete sidewalk, west of the House Office Building Annex, east side of South Capitol Street, and about 184 ft south of the south curb of B street, and three ft east of a temporary bench mark that is 4 inches lower than Station 1. The temporary bench mark is a chiseled (+) on the east curb of South Capitol Street. Station 1 is located 65 ft due west of and at an elevation 11.5 ft higher than the top of the brick pier for Station 21 of the U. S. Coast and Geodetic Survey in the Pendulum Room in a sub-basement of the former USC and GS office building at 205 New Jersey Avenue, SE., which building has now been replaced by the larger, more massive House Office Building Annex. Special data from the USC and GS give the elevation of the temporary bench mark described as 55.92 ft, and the elevation of the top of the brick pier for USC and GS Station 21 as 44.74 ft.

Station 2 was located on the concrete floor between two concrete piers in the Pendulum Room (Room B817) in the southwestern part of the basement of the building of the United States Department of Commerce; about two feet due east of and at an elevation 2.0 ft lower than the top of the concrete pier for USC and GS Base Station 337.

Station 3 was located on the concrete floor in the small south room used by HEYL and COOK [1936] for the absolute gravity determination in the constant temperature vault in the sub-sub-basement of the East Building at the National Bureau of Standards; about two ft southwest of and at an elevation about 1.5 m lower than the mean center of gravity of Heyl and Cook's pendulums as judged from the photograph [HEYL and COOK, 1936]. The USC and GS Pendulum Statio 84A, established by BROWN [1936] in 1932 was located on the concrete floor in the larger adjoinin room; about 10 ft northwest of and at the same elevation as gravimeter Station 3. The elevation o Station 84A as given in Brown's report is in error. Original records at the United States Coast and Geodetic Survey show the elevation of Station 84A to be 310.87 ft instead of 297.9 ft, as reported by Brown.

Observations--For a check on the precision of the readings, the gravimeter observations were made in a closed loop. The gravity difference between each pair of stations, commonly called a "leg", was determined independently by making alternate observations with the gravimeter on the two stations before proceeding to the next leg. The scheme of operation and the gravimeter readings are indicated in Figure 1, in which successive readings at one point are connected by lines to indicate the instrumental drift. The instrumental performance may be judged by the parallelism of the various segments of the drift curve. The observed difference between the stations, in scale divisions, is calculated by subtracting from the reading at one station the "zero reading" at the other station, as interpolated by the plotted drift curve. The data provide two, not entirely independent, determinations of each gravity difference as indicated by the dashed vertical lines in Figure 1.

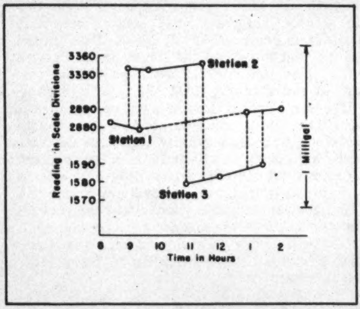

Figure 1--Plot of gravimeter readings

Table 1--Gravity differences by gravimeter

Leg		
1 to 2	2 to 3	3 to 1
mg	mg	mg
+ 5.26	- 19.72	+ 14.46
+ 5.26	- 19.72	+ 14.44
+ 5.26	- 19.72	+ 14.45

Error of Closure = $\Sigma\Delta g$ = 0.01

The differences in scale divisions are converted to gravity units by a "scale constant" determined by calibrating the gravimeter on a known gravity difference of about 27 mg, which had been measured to a probable error of ±0.2 per cent with Gulf pendulum apparatus [GAY, 1940]. The gravimeter calibration was checked both before and after the trip to Washington and the change was less than 0.1 per cent which is not significant. The gravimeter results are shown in Table 1.

The precision of the measurements, as judged by the internal consistency, and the error of closure, is as good as could be desired. The accuracy is undoubtedly limited by the uncertainty in the absolute value of the calibration which may be, say, twice as large as the probable error of the gravity difference used for the calibration, or about 1/2 per cent. Since the present gravimeter measurements cover a range of only about 20 mg, the observed gravity differences are not likely to be uncertain by more than about 0.1 mg.

Reduction of gravimeter data to pendulum stations--Since the gravimeter readings were not taken at the identical sites of the pendulum stations which it was desired to recover, corrections must be applied to the gravimeter results to refer them to the sites of the pendulum stations.

The corrections for the gravitational effect of nearby masses being quite small, it is necessary to evaluate them only very approximately. At Station 1, the corrections for both building masses and excavations were evaluated by use of the author's Terrain Correction Tables [HAMMER, 1939] subdivided, and extended in the inner zone. The mass of each building was assumed to be uniformly disseminated through the volume of the building with a density of 0.25. At Station 2, the relative effect of adjacent building masses was neglected, as the gravimeter and pendulum observation sites were practically identical. At Station 3, the relative corrections for the building mass and surface terrain were neglected, and the relative corrections for the excavations for the sub-sub-basement, taken as 16 ft x 16 ft x 30 ft deep, were evaluated semi-graphically from the calculated attraction of a thin square plate. The calculated corrections are given in Table 2.

Table 2--Calculated corrections to gravimeter data

Station	Item	Correction
		mg
1	Correction, mass of old buildings on USC and GS No. 21	- 0.07
	Correction due to unexcavated earth (density = 2.0) outside old buildings on USC and GS 21	- 0.14
	Correction for mass of House Office Building Annex on Station 1	+ 0.05
	Correction for "terrain" [principally basement excavation for House Office Building Annex (density = 2.0)] on Station 1	+ 0.03
	Bouguer correction (density = 2.0) for elevation difference from Station 1 to USC and GS 21	+ 0.79
	Total	+ 0.66
2	Free air correction for elevation difference from Station 2 to USC and GS 337	- 0.19
3	Station 3 to USC and GS 84A: relative proximity effect of excavated masses (density = 2.0)	+ 0.05
	Station 3 to Heyl and Cook's absolute gravity station:	
	(a) Relative proximity effect of excavated masses (density = 2.0)	- 0.06
	(b) Bouguer correction for elevation difference (density = 2.0)	- 0.34
	Total	- 0.40

Final results--Applying these corrections to the data in Table 1, we find gravity differences between the USC and GS Base Stations in Washington as shown in Table 3.

Table 3--Gravity differences between base stations in Washington

From	To	Difference	Total Difference
		mg	mg
USC and GS 21	USC and GS 337	+ 5.26 - 0.19 - 0.66	+ 4.41
USC and GS 84A	USC and GS 337	+ 19.72 - 0.19 - 0.05	+ 19.48
USC and GS 84A	USC and GS 21	+ 14.45 + 0.66 - 0.05	+ 15.06
USC and GS 84A	Heyl and Cook's absolute gravity station	- 0.05 - 0.40	- 0.45

The gravimeter results and previous pendulum ties are summarized schematically in Figure 2. The arrowhead on each leg points in the direction of increasing gravity.

The gravimeter differences, together with an adopted value at one point, give gravity values at the various base stations as shown in Column 3, Table 4.

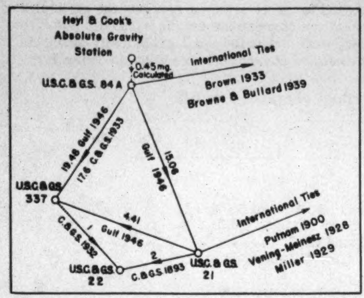

Fig. 2--Schematic gravity base station net in Washington, D. C., gravity differences in mg

Table 4--Gravity values

Station	USC and GS value	Gulf value	Difference
84A	980.100	980.1000[a]	. . .
21	980.117	980.1151	-.0019
22	980.119	980.119[b]	.000
337	980.118	980.1195	+.0015

[a] Adopted. [b] Average using USC and GS pendulum ties from Stations 21 and 337 with arbitrarily assigned weights of 1 and 2, respectively. The uncertainty in the value may be as large as ± 2 milligals

Discussion--The results of this work differ appreciably from the previous pendulum ties between the gravity base stations in Washington, D. C. The gravity difference determined in the present work from USC and GS Station 21 to USC and GS Station 337 is 3 1/2 mg larger than the old indirect pendulum determination via USC and GS Station 22. Therefore, the relative values on these three base stations as used by the USC and GS are uncertain to about this amount. It may be worth while to reconsider the relative values on pendulum stations set out from these three bases.

The gravity difference from USC and GS Station 84A in the National Bureau of Standards to USC and GS 337 in the building of the United States Department of Commerce, as determined in the present work is nearly 2 mg larger than the USC and GS pendulum determination in 1933. This is an unexpectedly large discrepancy considering the apparent precisions of the two sets of data. The probable error of the pendulum difference, estimated from the internal consistency of the data as given in Table 3 by BROWN [1936], is 0.6 mg, but the "scatter" of the individual values is very large. The present gravimeter tie can hardly be in error by more than about 0.2 mg; 0.1 mg for a possible, but improbable, absolute error in the calibration and 0.1 mg for errors in the gravimeter readings and their reductions. The data have been checked carefully for gross errors. The previous gravimeter tie in 1936, mentioned above in the introduction, also supports the present determination, as it gives a difference of 19.56 mg when the relative magnetic correction of 0.81 mg is applied with the apparently correct sign. This compares with the present determination between the same two points of 19.72 mg. The 0.16 mg discrepancy can be ascribed entirely to uncertainties in the magnetic corrections for the 1936 data [HAMMER, 1938, Gig. 6]. The conclusion seems inescapable that Brown's pendulum tie is in error by about 2 mg.

Probably the most important result of the present work is a direct and accurate determination of the gravity difference between the two base stations in Washington shown in Figure 2, which have been used for international gravity comparisons. The previously adopted value for this difference was based on old and indirect pendulum observations and the value commonly used seems to be 17 mg [LAMBERT, 1942; DRYDEN, 1943]. The present work finds the value of this difference to be two mg smaller, namely, 15.1 mg. The writer suggests that this value be used in comparing various international gravity values with the absolute gravity determination in Washington and in arriving at a World Gravity Net, such as has been proposed recently by MORELLI [1946].

Acknowledgments--Anthony Carnvale, formerly in charge of gravimeter construction at the Gulf Research and Development Company, and now at the Naval Ordnance Laboratory at Silver Spring, Maryland, arranged the details for the observations in Washington and operated the gravimeter. A large share of the success of the work is due to his generous collaboration. The precise location of Station 1 relative to the old Base Station USC and GS 21 was supplied through the courtesy of W. D. Lambert and H. S. Rappleye of the United States Coast and Geodetic Survey. Lambert also assisted at Station USC and GS 337. The observations at the National Bureau of Standards were made through the courtesy and with the assistance of F. B. Silsbee and L. B. Tuckerman. Drawings showing floor plans of pertinent buildings for calculating their gravitational effects were kindly supplied through the office of the Architect of the Capitol. Finally, thanks are due to Paul D. Foote, E. A. Eckhardt, and Leo J. Peters of the Gulf Research and Development Company for sponsoring this research.

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SEISMIC MEASUREMENTS ON THE ROSS SHELF ICE--Part I

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Abstract--Because of the possibility of using seismic equipment in the location of coastal outlines beneath the surface of the Antarctic ice, and for the purpose of making a detailed study of the little understood Ross Shelf Ice, a specially designed seismograph was included in the scientific equipment of the Byrd Antarctic Expedition II, 1933-1935. One hundred and twenty-two stations were occupied in the general area of the Bay of Whales from which it was possible to determine the thickness of the ice, tell whether it was floating or resting on the bottom, and if floating, what the depth of the water was, and something about the stratification of the bottom.

The northern edge of the Ross Shelf Ice from Kainan Bay to Discovery Inlet was found to be floating to a distance of at least ten miles south from its northern edge. The rise in the surface southeast of Little America in the otherwise relatively low level surface of the Ross Shelf Ice was for the first time definitely shown to be an island, although this had long been suspected. This island was subsequently named Roosevelt Island. The shelf ice for a distance of ten miles north of Roosevelt Island was found to be grounded, as was another area south of Amundsen Arm and west of the north end of Roosevelt Island. An accurate map of the Bay of Whales was constructed from vertical photographs, and a contour map of the bottom is superimposed on this map. The locations of the seismic stations are also shown. The seismograph has proved to be a most effective instrument for studying the Ross Shelf Ice, and it is recommended that future expeditions into the Polar regions should include such an instrument in their scientific equipment. A second paper pertaining to stratification and to clues concerning glacial moraine and their effect upon the origin and movement of the Ross Shelf Ice, as determined by seismic measurements, will be presented later.

Introduction--Perhaps no continental outline has been the subject of more speculation on the part of the explorers than has that of Antarctica. In no section of the region has there been as much known about the surface features, and so much elaborate interpretation concerning their origin and persistence based on conditions assumed to exist below the ice and snow, as is the case for that area between the 600 mile long vertical ice wall that stopped Sir James Clark Ross in 1841, and the Queen Maud Mountains 400 miles to the south. More flying has been done over that section and more sledging parties have traversed it than any other section of the Antarctic; yet the literature dealing with its interpretation is characterized by the unreliability of observations, the magnitude and complexity of the interpretations, and the positiveness of the convictions thus formed. The depth of the water along the front edge of the Ross Shelf Ice, or the Ross Ice Barrier, clearly shows that its northern edge is afloat. The vast extent of comparatively smooth level surface at relatively low elevation has led to the conclusion that the major portion of it is afloat.

The elevation of certain isolated portions of the shelf ice would indicate a tremendous ice thickness or that it is grounded either above or below sea level. The existence of badly crevassed areas in a region completely surrounded by comparatively smooth ice with the surface all at about the same level, the crevassed region extending for more than 100 miles south from the Bay of Whales and the persistence of such features along the barrier wall of Kainan Bay, the Bay of Whales, Lindbergh Inlet, and Discovery Inlet have been the topic of much consideration.

These and many other questions concerning this region, to say nothing of the polar plateau, led us to include in the scientific equipment of the Byrd Antarctic Expedition II, a geophysical instrument, new in Antarctic exploration, with the hope that we might make a beginning toward solving some of these most interesting problems. The instrument used for this work was a seismograph designed especially for us by William Green, then with the Seismograph Service Corporation.

The seismic equipment--The limitations imposed by the necessity for transporting the equipment over many miles of Antarctic snow and ice, and operating it at a very low temperature in the absence of dark room facilities on the trail, presented some difficult problems of design and mounting. In addition to making the equipment very light and rugged, it was necessary that it be very sensitive so as to make it possible to obtain good reflections with very small charges of Trojan powder or TNT, thereby increasing our operating radius by further decreasing our load. These explosives were used because of the safety of handling them, and their dependability at the extremely low temperatures.

This seismic equipment was taken on more than 2000 miles of travel by dog team, tractor, plane and boat in actual operation in the Antarctic. The instrument was never once thrown out of adjustment, nor a single suspension broken in the five element oscillograph, even though the sled on which it was mounted broke through the thin snow bridge over several crevasses and had several nasty spills in pressure-ice areas. On one occasion it was transported by dog team for more than two miles over loose pieces of floating bay ice, the pieces of ice being pulled close enough together so that the dogs could jump from one piece to the next in order to reach the Bear of Oakland in Discovery Inlet and put the party and equipment aboard.

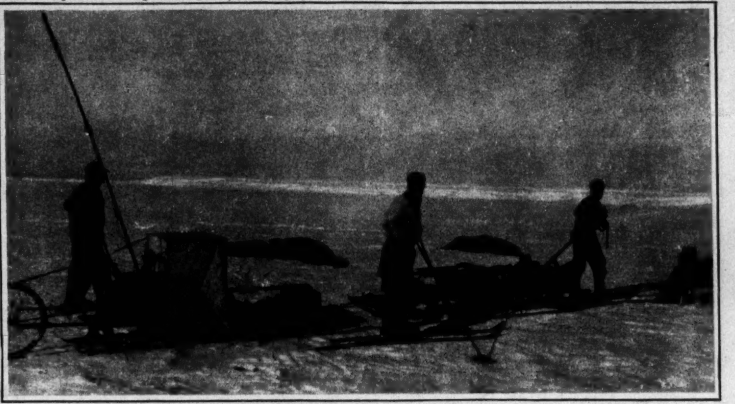


Fig. 1--Seismic equipment on trail (Note Weddell seals asleep in the background)

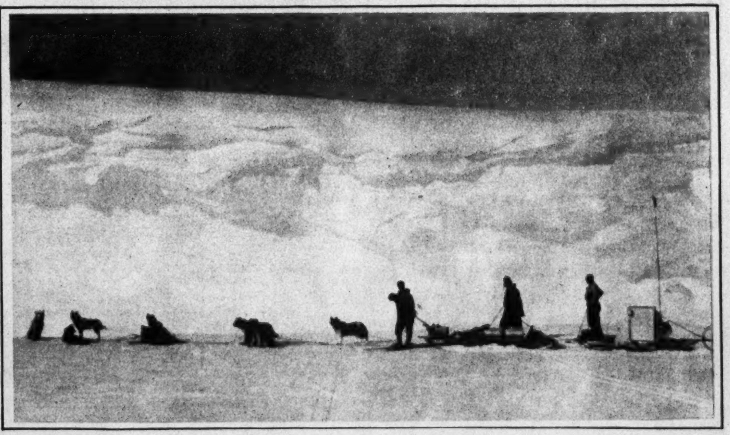
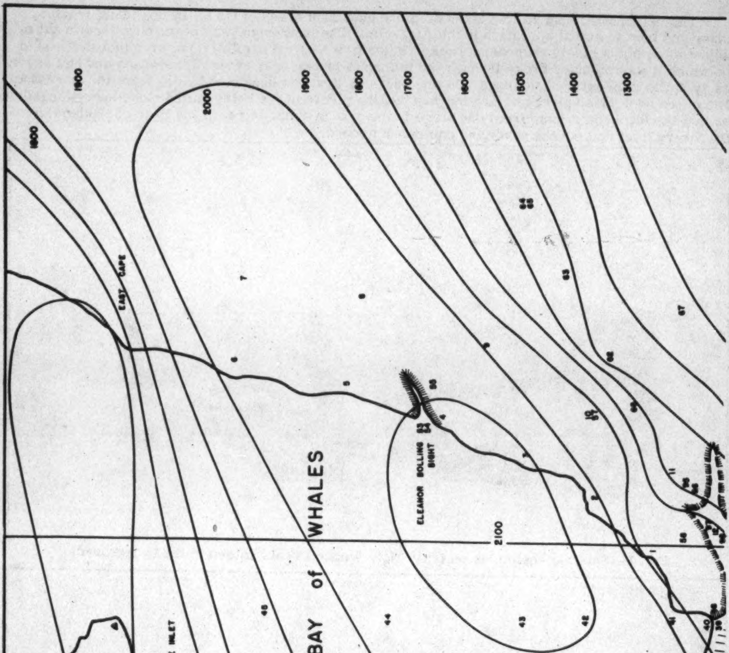


Fig. 2--Seismic party in Sunny Side Inlet

The camera, oscillograph, amplifiers, control unit, timing fork, shielded battery box, and geophones were taken to the Antarctic as separate units and mounted in a single trail instrument as shown in Figures 1 and 2. Preliminary experimental work had been carried on to determine the


ROSS SEA
WEST CAPE
SUNNY SIDE INLET
EAST CAPE
BAY of WHALES
KENNETT BAY
FLOYD
CHAMBERLAIN HARBOR
ELEANOR BOLLING BIGHT
2100
2000
1900
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1700
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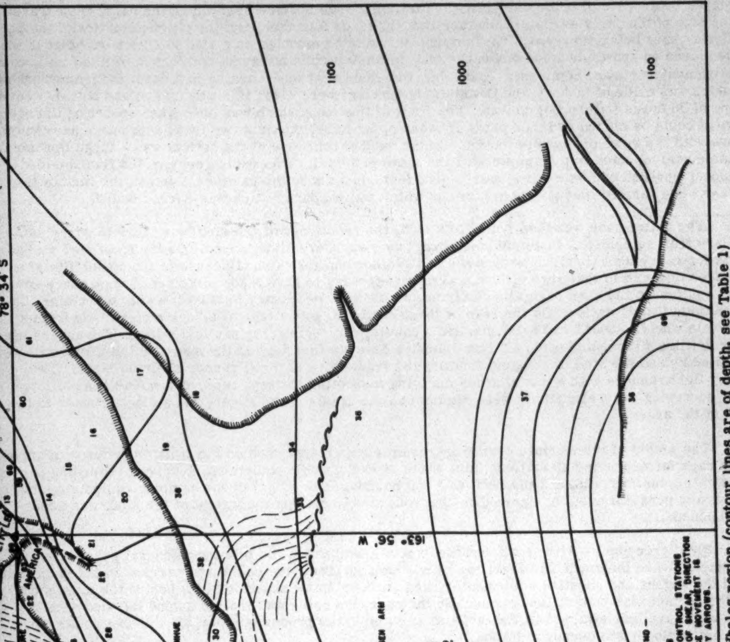
78° 34' S
163° 56' W
LITTLE AMERICA
PRESSURE ICE
PRESSURE ICE
CAPE MANHUE
AMUNDSEN ARM
NAUTICAL MILES
0
1
2
- LEGEND -
O HAY COCKS
△ SURVEY CONTROL STATIONS
LINE OF SHEAR, DIRECTION OF ICE MOVEMENT IS INDICATED BY ARROWS.
2000
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1100

Fig. 3--Bay of Whales region (contour lines are of depth, see Table 1) most suitable arrangement for rapid and efficient operations. It was necessary that the system employed be a rather flexible one to fit the particular type surface over which the party must travel, the size of the party available, whether two, three, or four men, and the characteristics of the particular area being surveyed. The instrument had to be mounted on a sled in such a way that it could be closed up snowtight when out on the trail in an Antarctic blizzard, and that is in itself an accomplishment worthy of comment. To do this, the equipment was mounted in a case, the framework of which was made of hickory and Dowmetal bolted together. Over this was tacked and bolted a covering of 36 ounce waterproof canvas. The front of this case which was open when operating the equipment could be closed by three pairs of overlapping flaps, the first two fitted with snaps and the other one with two rows of rawhide thongs. On the back of this case at the bottom was a large Dowmetal cable reel mounted in a framework of the same material. This cable reel carried five shielded rubber covered cables totaling nearly 4000 feet. Just above the cable reel and on the back of the case were carried four geopnones, one of which was a spare, which was never needed.

The entire case was then bolted to a sled, the remainder of the sled being free to carry auxiliary trail equipment. In actual operation, two sleds were always used. On the front sled was a box for carrying a supply of explosives and another one for caps. Because of the possibility of a sudden blizzard in that region, it was always necessary to have a complete set of emergency camping equipment and such navigation instruments as were necessary to travel, and to determine the position of each station. On the rear of the second sled was a typical sledge meter made from a bicycle wheel to which had been attached a counter for registering nautical miles. The augers used for drilling a three and one-half inch diameter hole six feet deep in the snow for the explosives were trailed behind the sled, the augers forming the framework of three runner skeleton sleds. Two very light runners with a box attached carrying a shooting battery, caps, and explosives sufficient for occupying several stations were clamped to the handle of the auger, and a single runner to the bit of the auger.

The weight of the seismic equipment, complete as it was used on the trail, including explosives and caps for occupying 25 stations (four shots at each), radio equipment, supply of recording paper, navigating instruments, and the sled, was 550 pounds. The weight of the camping equipment, dog food, and personal supplies carried on the front sled, including the weight of the sled, was about 400 pounds.

Field procedure--After considerable experimental work, the following general procedure was adopted. When the outfit was traveling over rough surfaces, the cable was carried on the large reel, and the augers and shooting equipment trailed on their small skeleton sleds behind the main sled. If the surface was smooth, as was usually the case, the cable was trailed behind the sled with the two auger trailers attached to the cable so as to be in the proper position for the shot points when the outfit stopped to occupy a station.

With a four-man party, one shooter would ski beside each of the two auger trailer sleds. The operator and assistant operator, on skis, drove the dog team and broke trail out in front of the dogs. When a stop was made, each man and whatever equipment and material he needed, were in correct position. The shot distances were measured on the cables, which were frequently checked for any stretching of the cable. While the two shooters were burying two or three charges in separate holes about six feet deep, the assistant operator placed the geophones in holes drilled two feet deep into the snow. The geophones were then covered with loose snow, and all cables within six feet of the geophones were covered with snow to prevent disturbances being produced by the wind vibrating the cable. It was necessary also that the snow surface in the immediate vicinity of each geophone be fairly smooth to prevent wind disturbances. The geophones were placed 200 feet apart and in the same straight line with the two shotpoints. The shotpoints were so spaced that the distances from the closest one to the three geophones were 400, 600, and 800 feet, respectively, and the distances from the farthest shotpoint were 1000, 1200, and 1400 feet. While the shooters and assistant operator were placing the charges and geophones, the operator recorded the necessary data for the station from which its position and altitude could be determined. Then, after checking his instrument panel, he adjusted the sensitivity of the geophone amplifier circuits, making use of the vibration produced by the assistant operator skiing back past the geophones. After making sure that the dogs were all quiet, the operator signaled over to the farthest shooter to stand by; then after starting to turn the camera, he signaled for the shot. The shots were fired in as rapid succession as the shooters could change their connections, and the operator and shooter exchange signals.

By the time the equipment was secured ready to travel, the geophones had been picked up and the small trailer sleds attached to the cable. The assistant operator usually served as dog driver, and the operator broke trail on skis to the next station. After becoming accustomed to the work it was not uncommon to occupy a station in as little as 15 minutes, and it seldom required more than 30 minutes. The greater portion of the time was therefore consumed in traveling from one station to another.

No attempt was made to develop the records in the field. The magazine containing the exposed records was removed and the records developed when the party returned to camp. By using a black cloth, lightproof changing bag, the magazine containing the unexposed paper could be reloaded. In spite of the extreme glare from the sun and its reflection from the snow, the equipment was operated in the open at all times.

Details of survey--With the necessary experimental work completed, the routine field work was started on Thanksgiving Day, 1934. During the remainder of November, throughout December, and into January, the seismic party composed variously of Thomas C. Poulter, R. B. Black, Finn Ronne, Bernard Fleming, and E. L. Moody, covered about 1000 miles on skis with dog team, and about 1000 miles by plane in continuous operation of the seismic equipment except when forced by blizzards to camp in the field or remain in camp. During this period a large number of stations were occupied in the vicinity of the Bay of Whales (see Fig. 3), particularly east of the Bay, south on Cape Manhue, across Amundsen Arm and southeast to a point (78°52'S, 163°06'W) where the surface of the snow reached an elevation of 710 feet.

By this time the season for long exploration flights was over, and the Condor plane was then used to occupy a series of outlying stations extending from Kainan Bay (78°14'S, 161°55'W) which is about 24 miles northeast of the Bay of Whales (78°34'S, 163°56'W) south across the rough pressure ice east of Amundsen Arm to a point (79°06'S, 163°15'W) where the surface of the snow reaches an elevation of 1400 feet above sea level, then northwest to a point (79°00'S, 164°00'W) 25 miles south of Little America. Two more stations were then occupied in a southeasterly direction on a radius of about 25 miles from Little America and another station at a point (78°30'S, 170°55'W) just south of Discovery Inlet. A flight was then made to Bolling Advance Weather Base (80°08'S, 163°57'W), and on the return flight to Little America, a final station was occupied at a point (79°45'S, 164°00'W) about 75 miles south of the Bay of Whales.

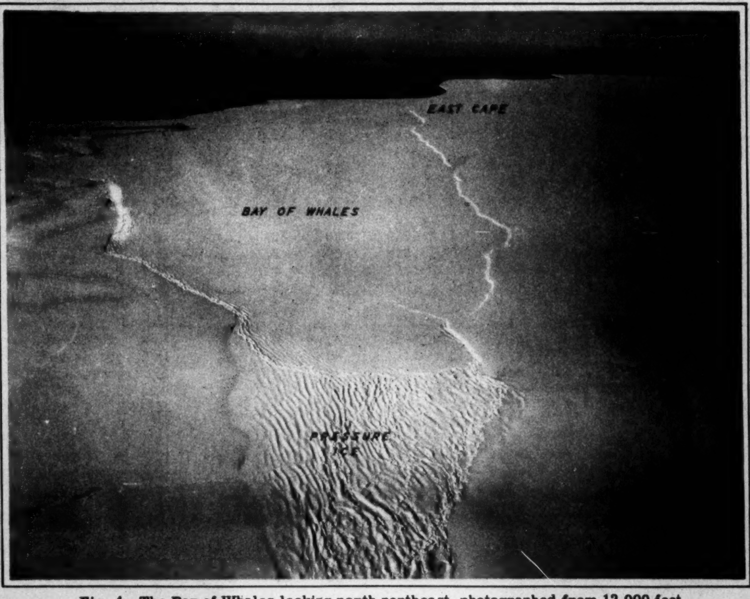

Fig. 4--The Bay of Whales looking north northeast, photographed from 12,000 feet

For the purpose of preparing an accurate map of the Bay of Whales and the surrounding area covered by the seismic survey, a Fairchild mapping camera was mounted in the Condor plane, and vertical photographs taken of the Bay of Whales area from an altitude of 12,000 feet. Several series of oblique photographs (see Fig. 4) were taken covering the area from Kainan Bay west to Discovery Inlet, which photographs gave considerable detail of an area of more than 3000 square miles. The map (Fig. 3) was made from aerial photograph mosaics, some of which were more than 23 feet in length.

In order to tie in more closely the stations occupied by the plane with those previously occupied, the seismic party, again traveling by dog team, occupied a series of stations extending westward from the Bay of Whales past Lindbergh Inlet (78°22'S, 166°30'W) to Discovery Inlet where a rendezvous had been arranged with the Bear of Oakland, returning from New Zealand to the Bay of Whales. The results obtained at these seismic stations are listed in Table 1.

As a part of the survey for the seismic operations, as well as for control stations for constructing the map of the Bay of Whales, a triangulation survey was made of all of the survey markers remaining of those set up by Blackburn and Coman during their survey for mapping the Bay of Whales in 1929-1930.

Good records were obtained at more than 95 per cent of the 122 stations occupied, in spite of the disadvantage imposed by not developing the records in the field, thereby not knowing whether a good record had been obtained before moving on to the next station. These records are unusual in many respects. Because of the spread of the shot points and geophones, values are obtained on each record for five points spaced 100 feet apart along a line joining the shot point and geophones. The consistency of the data is unusual; practically all cases where the difference between the maximum and minimum value obtained for the depth of the ice or water was more than one per cent,

Table 1--Results of seismic observations

Station	Surface elevation	No. of values	Average ice thickness	No. of values	Average depth	Station	Surface elevation	No. of values	Average ice thickness	No. of values	Average depth
	ft		ft		ft		ft		ft		ft
1	55	5	910	23	1875	30	104	12	710	12	1312
2	44	5	509	9	2076	31	84	6	629	9	1411
3	55	6	760	12	2147	32	40	6	204	12	1439
4	46	5	625	9	2134	33	40	5	467	12	1186
5	72	6	610	9	2066	34	10	...	50	12	1230
6	72	2	841	2	2082	35	20	...	70	8	1110
7	84	4	899	3	2043	36	108	12	694	12	582a
8	108	...	...	...	...	37	10	...	50	11	870
9	98	5	622	2	2028	38	20	...	60	11	1359
10	78	3	718	2	1945	39	2	...	15	5	1949
11	88	7	863	12	1687	40	2	...	15	3	1904
12	10	...	...	10	1856	41	2	...	15	3	2036
13	84	11	770	10	1688	42	2	...	15	8	2171
14	108	5	612	10	1474	43	2	...	15	2	2165
15	108	5	616	15	1442	44	2	...	15	records lost	
16	108	6	714	13	1493	45	2	...	15	records lost	
17	89	7	531	9	1422	46	2	...	15	records lost	
18	108	10	592	12	1233	47	128	7	596	10	1657
19	69	6	528	10	1369	48	2	...	15	2	1850
20	98	6	689	9	1328	49	2	...	15	6	2035
21	98	7	721	12	1370	50	2	...	15	6	2099
22	40	6	289	12	1806	51	2	...	15	3	2043
23	69	9	569	12	1710	52	2	...	15	6	2056
24	89	6	604	11	1656	53	2	...	15	9	2200
25	79	3	552	6	1612	54	2	...	15	6	2199
26	68	4	624	4	1438	55	89	7	522	4	2052
27	103	9	688	12	1407	56	98	3	625	3	1958
28	89	8	803	12	1586	57	79	2	568	1	1969
29	104	2	981	12	1452	58	69	2	448	1	1750

Table 1--Results of seismic observations (concluded)

Station	Surface elevation	No. of values	Average ice thickness	No. of values	Average depth	Station	Surface elevation	No. of values	Average ice thickness	No. of values	Average depth
	ft		ft		ft		ft		ft		ft
59	80	6	560	5	1624	88	180	4	504	4	320[a]
60	89	6	627	2	1470	89	140	6	674	6	530[a]
61	94	6	1016	5	1368	90	140	5	494	5	350[a]
62	123	6	1008	4	1576	91	100	4	750	12	915[a]
63	118	6	966	4	1643	92	250	21	574	21	270[a]
64	128	5	1053	3	1620	93	150	...	...	2	738
65	118	...	...	...	... [b]	94	88	...	...	3	1713
36	98	2	727	2	1702	95	89	...	...	2	1688
67	84	...	...	...	... [b]	96	69	3	463	...	...
68	84	...	...	...	... [b]	97	20	...	...	3	1869
69	108	5	791	5	679[a]	98	20	...	...	2	1900
70	88	6	780	5	1107	99	30	...	...	3	1833
71	108	7	590	3	1091	100	2	1	15	...	...
72	93	6	566	4	878	101	2	1	15	...	...
73	86	4	530	2	665	102	147	1	631	2	1685
74	289	8	654	8	361[a]	103	155	3	579	3	1737
75	424	8	507	8	79[a]	104	160	1	754	3	1568
76	710	8	579	8	-135[a]	105	170	4	753	1	1615
77	100	8	728	6	1101	106	170	1	742	2	1500
78	139	7	638	9	1208	107	3	1	30	1	1510
79	50	6	364	5	1171	108	140	3	804	3	1507
80	98	1	1062	2	1200	109	170	3	824	1	1586
81	108	6	631	2	1280	110	170	2	889	3	1602
82	118	2	692	1	1332	111	140	1	820	1	1660
83	35	6	497	6	1802	112	150	3	914	3	1682
84	180	2	841	2	1798	113	147	6	824	4	1623
85	220	3	918	3	918[a]	114	117	2	850	2	1605
86	720	6	690	18	- 34[a]	115	3	1	30	3	1969
87	1400	20	554	20	-850[a]	116	3	1	30	3	1930

Elevation and depth are measured from sea level. A negative sign (-) preceding the value for average depth indicates that the land is above sea level.

No records were obtained for stations 8, 96, 100, and 101 because of an error on the part of the operator.

[a] Ice is grounded.

[b] Station was occupied for the purpose of determining the velocity of sound in the shelf ice and therefore no values for depth or ice thickness were obtained.

the profile map subsequently constructed shows that the slope of the bottom is sufficient to account for the spread in the values obtained.

At some stations the depth or ice thickness could be determined from as many as 14 points on a single record, with a maximum deviation of less than 0.1 per cent from the mean. It is quite unusual for the deviation from the mean to exceed 0.5 per cent. An average of 5.25 values was obtained for the thickness of the ice at each station and an average of 6.6 values for the distance to the bottom.

Such a large number of stations in the Bay of Whales area has made it possible to construct a contour map covering 125 square miles, and the outlying stations provide a great deal of information as to the profile of the bottom over an area of a few thousand square miles. Perhaps the most outstanding discovery resulting from these measurements was from the information provided by the series of stations from 70 to 76, inclusive, and 86, 87, 88, 92, and 93. As a result of information obtained from these, it was shown for the first time that the high snow area to the southeast of the Bay of Whales, which in some places reaches an elevation of 1400 feet, actually covers an island, the highest point of which is 850 feet above sea level. This island was subsequently named

Roosevelt Island, and is approximatley 90 miles long and 40 miles wide in its widest point. The northernmost end of the ice-locked island lies at 78°49'S, 162°00'W, and in December 1934, the closest point on the island to Little America was 78°50'S, 163°07'W, at a distance of 19 miles south southeast. The position of Little America at that time was shifting westward nearly six feet per day.

An examination of the contour map constructed from these data shows that the area of maximum depth extends across the bay in a northeast-southwest direction with a maximum depth of nearly 2200 feet. From this low, the bottom gradually slopes upward to the northwest about 100 feet per mile and upward to the southeast in the direction of Roosevelt Island 200 feet per mile. All of the ice immediately surrounding the Bay of Whales south to the southern edge of Amundsen Arm and the northern edge of the Ross Shelf Ice from Kainan Bay to Discovery Inlet is definitely afloat for a distance of at least ten miles south from the Ross Ice Barrier. The ice immediately south of Amundsen Arm and west of the north end of Roosevelt Island is grounded as is an area extending for ten miles north of Roosevelt Island, which accounts for the extensive crevasses in that area.

The average elevation of the surface of the floating shelf ice immediately surrounding the Bay of Whales is 94 feet, while its average thickness is 760 feet. This amounts to 12 per cent above sea level. Likewise, the average elevation of the shelf ice between the Bay of Whales and Discovery Inlet at a distance of a few miles south of its northern edge is 150 feet, with an average ice thickness of 820 feet. Thus 18 per cent is above sea level.

The difference in per cent of floating shelf ice above sea level is characteristic of the difference found between stations near the edge of a floating ice sheet as compared to points as much as a mile from the edge. Apparently the circulation of water under the ice melts it more rapidly near the edge, resulting in a corresponding decrease in buoyancy at that point. Then there results a settling of the ice along the edge. This curvature or slope of the top surface toward the edge provides a clue as to how long it has been since an iceberg has broken off the edge of the shelf ice, or the age of a large berg at sea.

Most of the seismic measurements contain considerable information about the stratification of the bottom, and this is being examined for possible clues for glacial moraine deposits and their effect upon the origin and movement of the Ross Shelf Ice. This will be discussed in the second of this series of articles dealing with the Ross Shelf Ice.

Conclusions--(1) The average elevation of the shelf ice surrounding the Bay of Whales is about 94 feet with an average ice thickness of 760 feet. (2) The average elevation of the shelf ice between Kainan Bay and Discovery Inlet is 150 feet with an average ice thickness of 820 feet. (3) The shelf ice between Kainan Bav and Discovery Inlet is floating for a distance of at least ten miles south. (4) The rise in the shelf ice surface southeast of Little America was definitely shown to be an island, ano named Roosevelt Island. (5) The shelf ice is grounded for a distance of ten miles north of Roosevelt Island. (6) The shelf ice south of Amundsen Arm and east of the north end of Roosevelt Island is gounded. (7) A contour map has been constructed which shows a maximum depth of nearly 2200 feet at Eleanor Bolling Bight with a low extending in a northeast-southwest direction from which the bottom slopes up to the northwest and up to the southeast in the direction of Roosevelt Island. (8) A current under the ice varying from zero to more than one knot from the northeast enters the Bay of Whales parallel with the low mentioned above, and leaves the Bay in a southwesterly direction. (9) No instrument in Antarctic exploration has answered more puzzling questions about the Ross Shelf Ice than has the seismograph, and much additional information is being obtained from these records. With the procedure now worked out for operating such equipment on a polar ice cap, and for interpreting the data thus obtained, it is strongly recommended that future expeditions into the polar regions include such an instrument in their scientific equipment.

Acknowledgement--The author wishes to express his appreciation of the assistance in the form of a grant from the National Research Council to assist in the purchase of this seismograph and for a fellowship from the John Simon Guggenheim Memorial Foundation under which this field work was carried on. On this work, the author was senior scientist and second in command, Byrd Antartic Expedition II.

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A PORTABLE STATIC DISCHARGE TOTALIZER

Ronald L. Ives

Abstract--Simple equipment for totalizing the number of static discharges through a neon glow tube or similar intermittent illuminations is here outlined, with salient constructional features.

Introduction--Field investigation of the rate of replenishment of the static charge on an insulated pickup device [see "References" at end of paper, IVES, 1946] disclosed that neither high resistance moving-coil instruments nor vacuum tube voltmeters were satisfactory for long-term tests, most of them being completely disrupted by heavy discharges after a short period of use.

Measurement by counting of the frequency of illumination of a "resistorless" type neon lamp connected from the pickup device to ground, however, was electrically satisfactory, had a relatively long service life and a low replacement cost (nine cents), but placed a severe strain on the operator. When the average flashing rate was slower than about five per minute the operator's attention lapsed, and when faster than about three per second overran the observer's reactions.

Automatic counter--Direct connection of the pickup device to any ordinary vacuum tube relay circuit invariably leads to disruption of the vacuum tube and usually of other circuit components by heavy induced charges. An indirect system was developed, consisting of a neon glow lamp (NE_1, see Fig. 1) which converts the static discharges into weak light, and a conventional photocell-vacuum tube-relay-counter circuit which converts the luminous pulses into numerical increments on the counter odometer. This circuit, which closely resembles the conventional "proprietary" photocell arrangement, is shown in Figure 1.

The neon bulb NE_1 through which the static discharges take place, and the photocell, are mounted in a light shield which may be any standard radio shield can of convenient dimensions. Value of the triode grid resistor R_1 is determined by the tube constants and sensitivity desired, as is the resistance of the plate relay coil. To absorb the inductive kicks produced when the

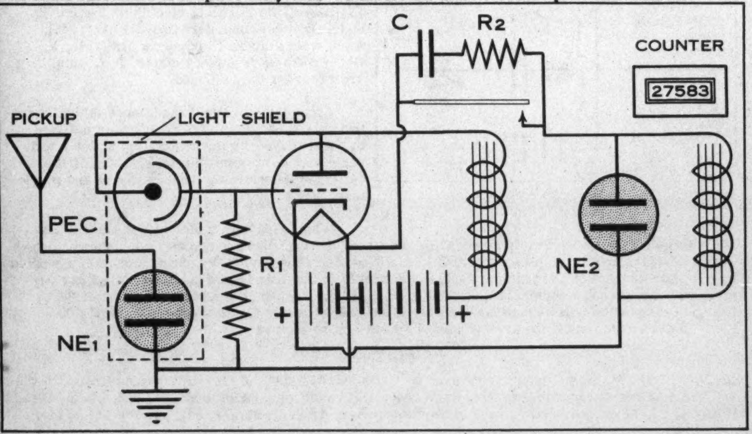

Fig. 1--Circuit diagram of photoelectric counter

counter magnet circuit is opened, a neon bulb NE_2 is shunted across the coil. This "depeaks" the kick to the extinction voltage of the neon bulb, provided the maximum kick potential exceeds the striking voltage. A conventional condenser-resistor spark absorber (C, R_2, Fig. 1) is connected across the plate relay contacts. This spark absorption not only extends the life of the relay contacts by a large factor (such as five) but makes operation of radio equipment in the near vicinity possible.

Using standard vacuum tubes and a "Raysonde" type battery, sufficient for about five hours of continuous operation, this counter can be constructed in a standard 5″ × 6″ × 9″ radio shield can. With full-sized batteries such as a six-volt "hot shot" for filament supply and a plate battery of similar dimensions, 50 or more hours of continuous operation are possible, and the device can be built in a case approximately 8″ × 10″ × 12″. Mechanical design is not critical; several alternative electrical designs are workable; use of special "midget" tubes and other components will increase operation time for a given set of batteries, but will usually be accompanied by a disproportionate loss of dependability and ruggedness.

Thyratron operation--Using a war-developed thyratron, it was found possible to eliminate the plate relay from the circuit and operate a counter directly from the thyratron plate current, eliminating all contacts, provided the frequency of incoming impulses was relatively low (such as one per second).

The chief obstacle to use of D. C. thyratrons in circuits of this type has been the difficulty of stopping the flow of plate current once it has started. By operating the counter from the stored energy in a condenser (see Fig. 2), which recharges relatively slowly from the plate battery, through a high resistance, reduction and stoppage of the plate current flow is obtained automatically.

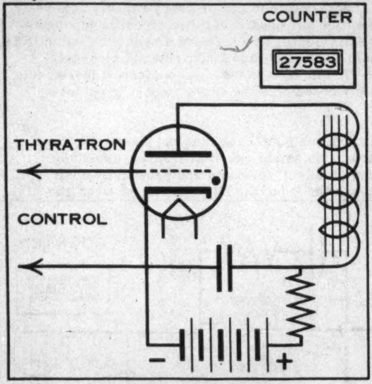

Fig. 2--Reservoir circuit for thyratron operation

Tests with this circuit, using experimental components, indicate that, while it will probably be standard for this type of service within a decade, it cannot be depended upon with components currently available (1946).

Recording--Where static charge renewal rates are very high, as during sandstorms in desert regions or ice storms in some of the higher mountain areas, chart recording of the rate of charge renewal is possible by use of a high-speed relay, such as a Stevens-Arnold "Millisec," in the plate circuit of Figure 1, and a Grinnell recorder [GRINNELL, 1945]. Also, where adequate power is available, a General Radio frequency meter, D. C. amplifier, and recorder may be used.

Conclusions--Field experience indicates that this static discharge counter, as outlined in Figure 1, performs dependably under a wide variety of conditions, the service life of the batteries determining the duration of any single test.

When used with a high-speed plate relay and a Grinnell Recorder or other recording frequency meter, discharge rates that "overrun" the response of the counter can be recorded. Simplification of the device, by use of a counter operated by the plate current of a thyratron, seems practicable in the near future but does not appear possible with equipment commercially available now (1946). Results of a number of tests made by this general method will be comparable only if the pickup device has the same electrical dimensions in each case, and if the ground used for each test is good.

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METEOROLOGICAL FACTORS INFLUENCING AIR POLLUTION IN THE LOS ANGELES AREA

Charles G. P. Beer and Luna B. Leopold

Abstract--The Los Angeles area is faced with the problem of planning the mitigation of air pollution. The meteorological factors which determine the distribution of the pollution and the intensity of the nuisance are the height of the prevailing summer subsidence inversion and the local sea-land breeze regime. Data on details of the wind structure and visibility are presented. These, with the time variations of the inversion, are discussed in relation to the pollution problem.

Introduction--In common with many other expanding metropolitan areas, Los Angeles has encountered the problem of increasing nuisance from smoke and other types of air pollution. The recent war period led to an acceleration of industrial growth, and the air pollution is now recognized as a definite problem. Not only is the City of Los Angeles affected, but many of the surrounding suburbs become acutely aware of the problem at times when weather conditions bring the pollution into their vicinity.

The most serious complaint has been smarting or irritation of the eyes noticed by many people in the affected areas on a few days each year. There is also the presence of smoke in some amount, although this is not as serious a problem as it would be in a region where coal is used as a common fuel. However, the reduction in the amount of light caused by passing through a widespread layer of smoke is a noticeable loss in a community where outdoor living and sunshine are such valuable assets. Although the complete abatement of smoke may prove uneconomical in any city, it can be shown that proper consideration of meteorological features in city planning would do much to reduce the nuisance.

The problem of air pollution around Los Angeles involves not only the location of the sources and measurement of amounts of impurities, but also the effect of certain climatic and weather features of the area. Among these are the prevalent low stratus cloudiness of summer, the possible presence of quantities of condensation nuclei derived from the nearby ocean (see Fig. 1), and the sea breeze, a daily occurrence of great regularity most of the year. It will be the primary aim of this paper to point out some of the controls which weather conditions exert on the distribution of air pollution, both horizontally and vertically.

Even if the pollution were entirely prevented, the Los Angeles area would experience a large percentage of low cloudiness and fog in the summer season. This is associated with the position of Southern California in relation to the semipermanent high-pressure cells over the Atlantic and Pacific Oceans and the ocean currents along the coast. A similar climate prevails in other parts of the world situated in analogous positions; namely, the areas around Casablanca, North Africa; Cape Town, South Africa; and Valparaiso, Chile. The frequent occurrence of fog and clouds in such areas is to be distinguished from what may be termed "air pollution." In this sense the term "air pollution" correctly implies materials which would not be found in the air in the absence of human activities.

Because the smoke pall so often occurs in combination with the summer fog and stratus, and at times even looks like a fog bank, it has sometimes been called "smog." This has unfortunately created some confusion as to the nature of the nuisance. The presence of smoke probably causes the formation of slightly more fog than would otherwise occur, but this has not yet been demonstrated from the available climatological records.

Meteorological aspects of the pollution problem

The effects of air pollution in Los Angeles are especially aggravated by two climatic features of the area. These are the temperature inversion and the local winds. As will be shown later, the local winds determine the horizontal distribution of the smoke by carrying it along in the air stream, that is, by advection. The vertical distribution of the pollution is limited by the persistent temperature inversion, beneath which the air is continually stirred by vertical convection and frictional turbulence. As suggested independently by Fletcher and Smith [see "References" at end of

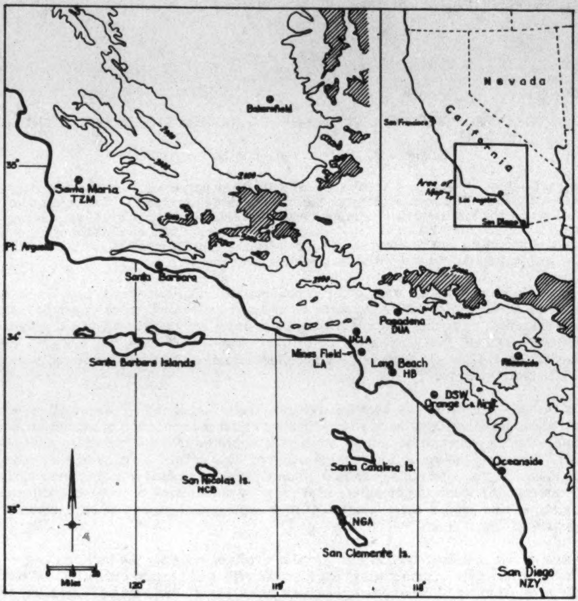
Nevada
California
San Francisco
Area of Map
Los Angeles
San Diego
Bakersfield
35°
Santa Maria
TZM
Pt. Arguello
Santa Barbara
Pasadena
DUA
34°
UCLA
Mines Field
LA
Long Beach
HB
Riverside
Santa Barbara Islands
DSW
Orange Co. Arpt.
Santa Catalina Is.
Oceanside
San Nicolas Is.
NCB
33°
NGA
San Clemente Is.
San Diego
NZY
Miles
120°
119°
118°

Fig. 1--Location map

paper, FLETCHER and SMITH, 1944; FLETCHER, 1945] the distribution of air pollution may be regarded as a combination of two processes, advection and convection.

Winds experienced in the Los Angeles basin are influenced by two factors. First, there is the local alternation between a sea breeze blowing toward the land and up the mountain valleys during the day, and a land breeze or down-valley wind during the night. These local winds will be discussed in more detail later. Second, there is the effect of the prevailing westerly winds of the temperate latitudes.

In summer the Los Angeles area is in the southerly fringe of the belt of prevailing westerlies, which, though they are rather light at this latitude, are still persistent enough to be called prevailing. The pressure gradient responsible for these winds tends to reinforce the sea breeze each day and to oppose the land breeze at night. A net transport of air from west to east results. Nevertheless, there are many times during the summer when this flow is reversed, especially at levels somewhat above the surface of the ground. Such reversals tend to aggravate the accumulation of impurities, since they do not allow them to be carried away in the general drift toward the east.

In winter the belt of westerlies shifts southward and brings the Los Angeles area under strong west winds for a larger part of the time. The temperature inversion is usually absent or quite high under these conditions. The smoke is then rapidly mixed through a deep layer of atmosphere, and advection carries it away in a relatively short time.

This general winter condition is frequently interrupted when a high-pressure center develops over North America and especially over the Great Basin. The prevailing westerlies may then be displaced at the surface by northeast winds and the inversion sinks to the surface and disappears. In such situations the smoke will be carried seaward at the surface.

These two conditions, either the prevailing westerlies or the east winds from a continental high, characterize much of the Southern California winter. It will be noted that under both conditions deep vertical mixing is possible because convection and turbulence are not limited by an inversion. This, in combination with the stronger winds, greatly reduces the effects of air pollution in winter. Summer is probably the season suffering the greatest overall nuisance, but spring and fall may bring a few days of acute conditions. These are due to the combination of a very stable summer-type inversion held to a low level by a winter-type circulation.

The temperature inversion

The characteristic summer temperature inversion is illustrated in Figure 2, a diagrammatic sounding showing the change of temperature with height through the lower atmosphere above Los Angeles in summer. The inversion is the layer through which the temperature increases with height. It is characterized by much greater stability (resistance to vertical motion or stirring) than the layers in which the temperature decreases with height. It thus tends to limit the height to which impurities are lifted from the surface.

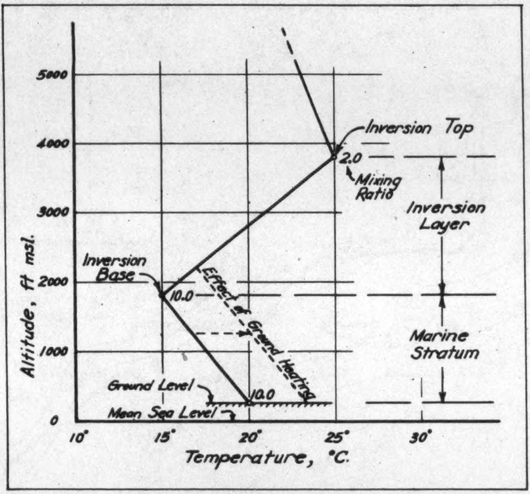

Fig. 2--Diagrammatic sounding

The point at which the temperature begins to increase with height is called the inversion base. It varies considerably in height during any one day and from day to day, and may even disappear entirely for a short time at the higher stations. Thus the thickness through which the pollution may be distributed is quite variable, giving rise to considerable variation in its concentration.

The point above the inversion base at which the temperature again begins to decrease with height is called the inversion top. Its height also varies considerably with time.

The layer of air beneath the inversion base may be called the marine stratum. It is unstable most of the time, resulting in continuous stirring which tends to produce a homogeneous mixture of water vapor, air, and any smoke or other impurities present. The air of the marine stratum has usually undergone recent travel over the ocean and its water-vapor content is therefore high, as shown in Figure 2 by a mixing ratio of ten g per kg at both the surface and the inversion base.

Air above the inversion top is characterized chiefly by its dryness. Although it may originally have been a maritime air mass, large-scale subsidence occurring in the subtropical belt of high pressure usually causes a change in its characteristics. It is preferable to refer to the air above the inversion as "superior" air, since this term is more descriptive of what happens when the inversion sinks low enough to allow the upper air mass to descend upon cities of the basin. This usually takes place several times each summer and is accompanied by a period of hot dry weather or "foehn." In the process of change from stratus or foggy weather to foehn conditions, contaminated air may be brought into areas normally free of pollution.

The mean height of the inversion base in the Los Angeles area is about 2000 feet msl but varies somewhat with distance inland. Some idea of the shape of the inversion surface can be obtained from Figure 3, which shows the average contours for the month of September, 1944. This Figure is taken from a previous report in which the shape and oscillations of the inversion have been discussed in greater detail [NEIBURGER, BEER, and LEOPOLD, 1945]. It can be seen that a slight trough in the inversion is present, roughly parallel to the coast and slightly offshore. The upward slope toward the land is caused at least in part by the higher surface temperatures attained inland as compared with coastal stations. The slope is important in that it allows a greater depth through which the pollution can be distributed in the eastern portion of the basin, toward which the pollution is blown by the mean wind flow.

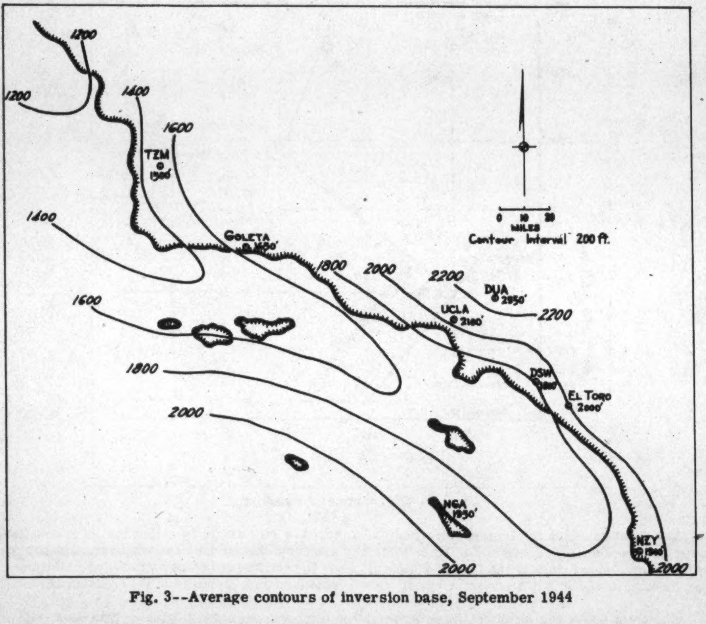

Fig. 3--Average contours of inversion base, September 1944

In summer the inversion is often wiped out in the eastern part of the basin and adjacent to the mountains by heating of the surface to a temperature considerably greater than that of the inversion top. When this occurs the pollution near the surface may be rapidly alleviated by convection through a thicker layer of air.

Figure 4 shows the change in height of the inversion base above Pasadena between August 31 and September 7, 1944. Both the diurnal and the long-period variations are apparent. The long-period changes are associated with convergence and divergence under the influence of moving troughs and wedges in the pressure patterns aloft [UNITED STATES ARMY AIR FORCES, WEATHER DIVISION HEADQUARTERS, 1945 a].

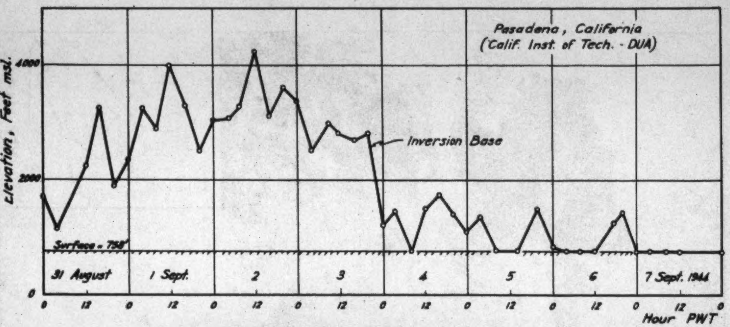

Fig. 4--Oscillations of inversion base

It can be seen from Figure 4 that during most of the 5th, 6th, and 7th of September, 1944, Pasadena was in the "superior" air mass rather than the marine stratum. The example is one of fairly rapid change from cloudy to foehn conditions, culminating in a temperature of 103°F on September 8, 1944. In other cases, when the inversion remains at elevations such as those on the 4th, the effects of air pollution may become quite noticeable at Pasadena. The impurities are then concentrated in a thin layer near the ground and may be associated with surface fog, as differentiated from stratus clouds or "high fog."

The diurnal variations in height of the inversion which can also be seen in Figure 4 result from the daily changes in solar insolation and the concomitant convergence in the sea breeze regime. The time of maximum height varies slightly from the coast inland [NEIBURGER, BEER, and LEOPOLD, 1945]. Stations near the coast such as Orange County Airport or UCLA experience maximum height at about $06^{h}00^{m}$ PWT, and minimum at about $18^{h}00^{m}$ PWT. Inland stations such as Pasadena have the maximum height near $14^{h}00^{m}$, again the effect of greater surface temperatures. These diurnal variations in the inversion height are responsible for corresponding changes in the severity of any pollution nuisance.

Land and sea breezes

Wind advection is the other factor which exerts a strong influence on the distribution of air pollution. The effect of the prevailing pressure gradient has been discussed. It was noted that this gradient is small in the seasons of worst pollution nuisance. A complete evaluation of wind advection must therefore include knowledge of the diurnal wind variations. All stations in the Los Angeles basin are influenced to some extent by the sea-land breeze regime characteristic of coastal areas. In general, they experience a southwesterly sea breeze beginning in the late forenoon and ending about sunset. During the night a lighter land wind from the northeasterly quadrant is the rule. The regime at each station is also influenced by local topographic features, but the alternation between day and night winds is apparent in all cases. Since it is sometimes difficult to determine whether a local wind is caused by the temperature difference between land and sea or that between mountain and valley, the terms "sea-valley" or "land-mountain" breeze will be applied to questionable cases.

Surface winds--The surface-wind pattern for each station is summarized in Figure 5, giving the average time of beginning and end of the prevailing wind directions in August 1944. Space limitations required the use of call letters to identify the observation stations. These are listed together with the station elevations in Table 1.

The daytime wind regime is indicated by the solid arrows in Figure 5. Wind directions characteristic of the late afternoon are shown with heavier lines. These represent the flow near the time of maximum sea breeze. It is immediately apparent from the overall picture of the afternoon sea breeze that the flow of air comes onshore approximately perpendicular to the local coast line, but is guided up the main valleys toward the passes. The flow splits into two streams, one stream flowing northwestward into the San Fernando Valley, the other eastward toward San

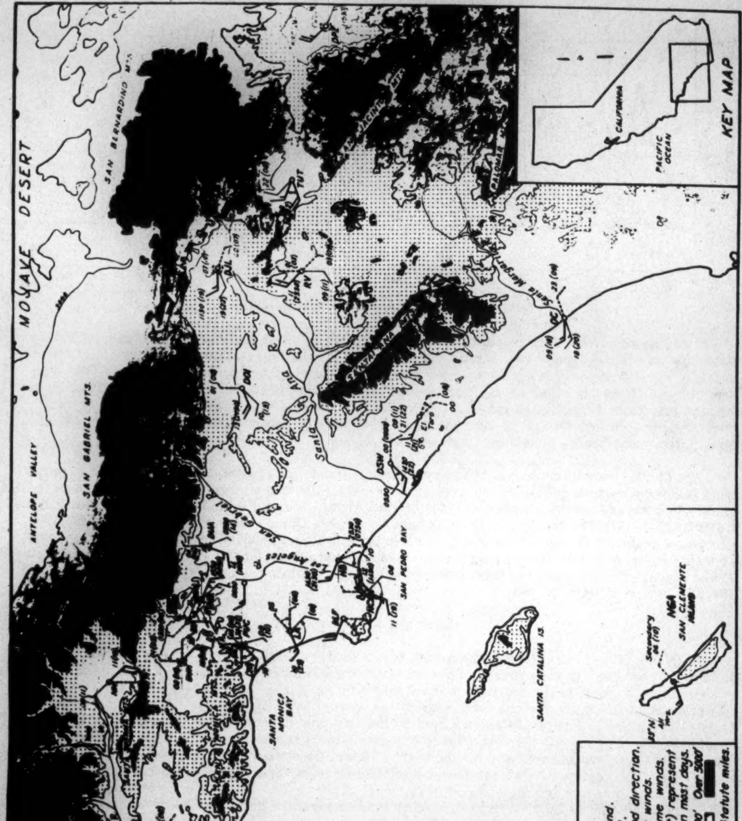
MOJAVE DESERT
SAN BERNARDINO MTS.
ANTELOPE VALLEY
SAN GABRIEL MTS.
SAN JACINTO MTS.
PALOMAR MTS.
SANTA ANA MTS.
TOPATOPA MTS.
Santa Clara R.
San Gabriel R.
Los Angeles R.
Santa Ana R.
Santa Margarita R.
SANTA MONICA BAY
SAN PEDRO BAY
SANTA CATALINA IS.
SAN CLEMENTE ISLAND
SANTA BARBARA IS.
SAN NICOLAS IS.
ANACAPA IS.
SANTA CRUZ IS.
KEY MAP
CALIFORNIA
PACIFIC OCEAN
LEGEND
STATION MODEL
PWT of beginning of wind.
PWT of ending of wind.
Gradual change of wind direction.
Dotted arrows are night winds.
Solid arrows are daytime winds.
Wind speeds (Beaufort) represent maximum speed attained on most days.
ELEVATIONS: 0-1000' 1-2000' 2-5000' Over 5000'
SCALE: 0 20 Statute miles.

Fig. 5--Diurnal changes of surface winds, August 1944

Gorgonio Pass. The sea-valley wind regime is felt at Palm Springs (DPZ) east of the San Gorgonio Pass and some 80 miles inland from the coast, and slightly affects the winds at San Clemente Island (NGA), 60 miles out to sea. San Nicolas Island (NCB), 80 miles from the coast, apparently is not subject to the diurnal shifts of the land-sea breeze regime.

Table 1--Call letters and station elevations

Station	Call letters	Elevation
		ft msl
Beaumont	TUT	2592
Burbank (Lockheed Air Terminal)	BU	725
El Toro (Marine Corps Air Station)		332
Glendale (Grand Central Terminal)	DGX	462
Lomita Flight Strip	DLF	106
Long Beach (Army Air Field)	HB	40
Los Angeles Airport (Mines Field)	LA	96
Los Angeles (Weather Bureau City Office)		512
Newhall	NH	1190
Oceanside	OC	10
Ontario (Army Air Field)	DOI	920
Orange County Army Air Field	DSW	52
Oxnard Flight Strip	DOC	82
Palm Springs (Army Air Field)	DPZ	420
Pasadena (Calif. Institute of Tech., CIT)	DUA	758
Riverside (March Field)	RV	1528
San Bernardino (Army Air Field)	DJL	1098
San Clemente Island (Naval Air Station)	NGA	906
San Nicolas Island (Naval Air Field)	NCB	505
San Pedro (Naval Air Station)	NCX	10
Santa Maria (Army Air Field)	TZM	229
University of California at Los Angeles (UCLA)	PUC	505
Van Nuys (Metropolitan Airport)	DVN	797

It will be noted that the night winds shown in dotted arrows are present at nearly all stations as far inland as March Field (RV) and seaward as far as San Clemente Island. These night winds are, however, weaker than the sea breeze at all stations. Their general pattern of flow is in the opposite direction to that of the sea breeze.

The details of the diurnal regimes at various stations are more complicated than the general picture just described. At some stations a westerly wind begins two or three hours after sunrise but comes from a direction slightly different from that of the maximum sea breeze. This early wind can usually be interpreted as a valley wind which commences earlier than the true sea breeze. Analysis of the diurnal changes at Orange County Airport (DSW) is typical of the reasoning which may be applied to many other stations. The sea-valley breeze begins at about $09^{h}30^{m}$ PWT from the west-southwest and backs gradually to southwest by $14^{h}30^{m}$. This change of direction is opposite that which would be expected as a true sea breeze approaches balanced flow. During the progress of the day the Coriolis force should tend to produce veering of wind at coastal stations. The west-southwest wind at the time of onset may be regarded, therefore, as the vector sum of a southwest sea breeze perpendicular to the coast and a west wind blowing into the valley east of Orange County Airport. The sea breeze effect increases as the day progresses, becoming dominant by $14^{h}30^{m}$ and continuing until two hours after sunset.

In general, the speed attained by the sea-valley breeze appears to be nearly the same at all stations. Since a true sea breeze should diminish in speed farther inland it is apparent that a merging of the sea breeze into the valley wind takes place. Noticeable increases in speed at a few stations (for example, DOI, NH, RV) are probably the result of channelization of the flow by topography rather than thermal effects.

It will also be noted that the onset of the sea-valley breeze at inland stations such as Newhall (NH) and March Field (RV) occurs only one or two hours later than at the coastal stations. This is insufficient time for the air which crossed the coast at the onset of the sea breeze there to have reached the inland stations. Moisture content of the air is, therefore, not a characteristic of the sea-valley breeze as defined in this paper. Fresh moisture will, of course, be carried inland by the sea breeze later in the day, but the change of wind direction may occur several hours before the arrival of new moisture at the inland stations.

The land breeze, being of smaller speed, is affected even more by the local topography. After the sea breeze dies down, a period of variable wind or calm usually ensues, followed by a drainage or mountain wind, later reinforced by the general easterly land breeze. For example, at Orange County Airport (DSW) the period of calms or variable wind lasts until midnight, when a definite east wind begins, continuing until the sea breeze starts at 09^h30^m. The cooling mountain slopes modify any tendency for a land breeze perpendicular to the shoreline.

The night-time current flowing southward out of the San Fernando Valley joins a broader easterly flow which crosses the coast along Santa Monica Bay. Cold air from the San Fernando Valley may account for the northeasterly beginning of the land breeze at Mines Field (LA), the wind veering gradually to east as the flow from the Santa Ana River basin increases.

Beaumont (TUT, 2592 feet), which lies in the mouth of San Gorgonio Pass, shows a diurnal wind regime quite different from the other stations. The predominant wind is not the sea-valley breeze but a lighter northwest wind which takes over as the sea-valley breeze diminishes around 22^h00^m. This northwest wind remains very steady throughout the night, but at 08^h00^m begins to back slowly, reaching west-southwest by 11^h30^m. At this time the full effect of the sea-valley breeze has presumably reached the station. Although the summit of the Pass is near Beaumont the surrounding ridges continue to rise for another 14 miles to the east. This favors the continuation of the afternoon westerly wind through the pass in spite of the descending valley floor, an effect sometimes termed a "Maloja wind." Narrowing of the valley toward the east end probably accounts for the high speeds of the wind reaching Palm Springs (DPZ).

These observations combined with pibals (pilot-balloon observations of upper winds) at DJL and RV indicate that the night-time layer of easterlies must become thinner toward the Pass, allowing a constant flow of the higher level westerlies through the Pass. At the eastern outlet of the Pass this westerly flow disappears by mixing into a southeasterly flow over Palm Springs.

Upper winds--The pilot-balloon observations taken at regular weather stations are not sufficient in number each day to allow analysis of the details of diurnal change. To collect data for such an analysis, a large number of slow ascent pibals were taken at the Army Research Weather Station, UCLA, under the direction of the authors in the summer of 1944. The balloons were inflated for a rate of ascent of about six feet per second and readings were taken at vertical intervals of 150 feet. The periods of observation were August 15 - November 20, 1944, during which 570 ascents were observed, and January 8 - 31, 1945, with 149 ascents.

The diurnal wind regime at UCLA studied in detail by these special observations is similar to that at most stations in the area, consisting of a sea breeze from the southwest during the afternoon and an easterly off-land wind during the night.

To illustrate this regime Figure 6 presents a time-height section of the winds observed at UCLA on September 1, 1944. Though no individual day shows all the features of the average picture, this day demonstrates some of the prevalent characteristics of the regime. During the period from midnight to noon the winds at the surface and in the lowest 2000 feet were east or southeast at small speeds, typical of the off-land night-time wind. At noon the surface wind veered to south, the characteristic harbinger of the sea breeze. The southwest sea breeze was well developed by 13^h30^m PWT below 2000 feet, while the easterlies persisted in a layer aloft. The sea breeze disappeared at the surface at 20^h30^m while still blowing aloft. By shortly after midnight the wind in the layer from 1000 to 2000 feet backed to southeast.

During the entire day the winds from 5000 to 10,000 feet were steadily from the northwest quadrant, thus emphasizing the reality of the easterly wind in the lowest levels. Though occurring on many days, a layer of east winds persisting during the entire day, as in the case of September 1, 1944, is by no means invariable. The time section has been analysed to show the separation of the easterly from the southwesterly winds in the lower levels, and the northwesterlies aloft.

The delineation of a sea breeze and a land breeze is not always easy, inasmuch as there is a transition zone between the sea breeze, land breeze, and upper flow, characterized by a gradual turning of wind with height. As an example, at 15^h00^m PWT September 1, 1944 (see Fig. 6), the east-southeast winds at 2000 feet backed gradually to northwest at 8000 feet. It is clear that the easterly winds represented the land breeze while the northwest or west-northwest winds predominating aloft throughout the day were part of the general circulation.

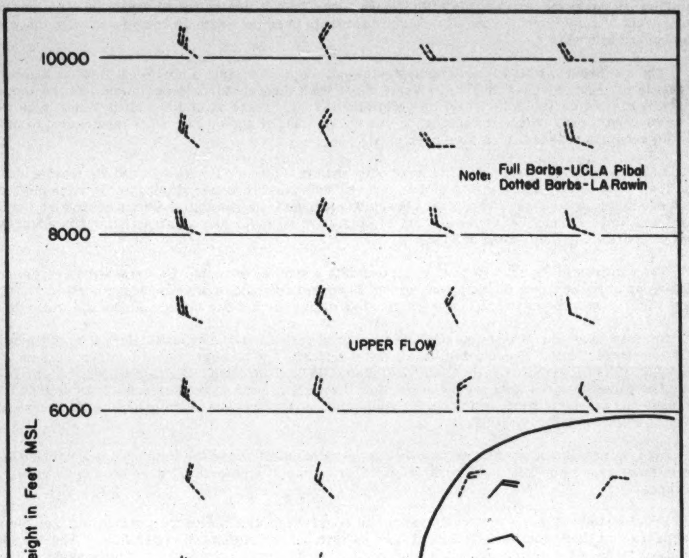

Fig. 6--Wind-time section, UCLA, September 1, 1944

The wind direction in the transition layer can be considered the vector resultant of an easterly component, the land-breeze effect, and a northwest wind vector representing upper flow. The increase of the northwest effect with height and the decrease of easterly component would produce the observed backing with height.

For the purposes of the wind-time sections in this paper the division lines between land wind and upper flow have been drawn to include winds from south-southeast to north-northeast in the land breeze zone, and north winds in the upper flow. This is equivalent to saying that the vector component of upper flow is considered to predominate over the easterly component when the wind has backed to north.

The sea breeze, which is ordinarily southwest, often veers into a northwest flow at higher levels in the same manner that the easterly winds back through north to northwest. In the present analysis of time sections, the solid lines defining the sea breeze at UCLA include winds from west to south-southwest. Where the transition was not distinct or where data were insufficient to place it with accuracy, dashed lines have been used.

In order to demonstrate the variety of patterns experienced, Figures 7a and 7b provide a time section for 24 consecutive days at UCLA. A relatively small number of wind arrows are plotted on these diagrams, but they have been chosen to represent the general condition of flow at that level and time. On most days the number of pibals available for the construction of the Figures was comparable to that shown in Figure 6.

The patterns in Figures 7a and 7b demonstrate a number of facts. Easterly winds representing the land breeze occur on every day except in unusual instances of very strong north or northwest winds. On some days the land wind persists aloft over the sea breeze during the whole day.

In some cases the sea breeze begins in the level just above the ground before it is discernible at the surface. This is presumably the result of friction, and has been noted in other regions [NAVAL METEOROLOGICAL BRANCH (BRITISH), HYDROGRAPHIC DEPARTMENT, 1944]. In very few cases does the land breeze begin aloft before it is seen at the surface. This results from the drainage mountain wind, which begins somewhat sooner than the more general land breeze and merges indistinguishably with it.

Also, in nearly every case, the sea breeze persists aloft above the land breeze. Not as often, but in many cases, the land wind persists aloft for a time after the sea breeze has begun at the surface.

From a study of these wind observations in conjunction with the corresponding weather charts, it appears that there are three layers of wind pattern below the general upper flow. The lowest and most local is the valley-mountain wind regime, controlled by the details of topography. The next is the sea-land breeze pattern, also characterized by a diurnal cycle, activated by the differential heating of air over land and sea. This regime is confined to the coastal plain and the ocean area immediately adjacent to the coast. Just above the sea-land breeze is the third wind pattern, controlled by the thermal low pressure over the southwestern deserts, and not confined to the coastal plain. On particular days the thermal low is definitely in evidence at 5000 feet not only during the daytime but for a portion of the night. It has a diurnal cycle of changing intensity, but at times exists at 5000 feet for a period of more than one day. The diurnal wind regime produced has been called a continent-ocean wind [UNITED STATES ARMY AIR FORCES, WEATHER DIVISION HEADQUARTERS, 1945 b]. At those times during which a low-pressure area over the land persists, the on-shore flow in the layer just above the sea breeze approaches the character of a true monsoon.

The general circulation aloft, which is little affected by the local heating of the coast line or the desert thermal low, prevails above the monsoonal winds.

There is ordinarily a gradual merging of each of these patterns into the one above it, but on certain days the effect of each layer can be definitely seen. If the inversion is wiped out along the mountain slopes by surface heating, resulting convection on such days may produce two or more layers of smoke over the Los Angeles basin.

Average diurnal wind regime at UCLA--In order to integrate the surface- and upper-air observations the average diurnal wind regime in height and time has been represented in Figure 8 for three periods, roughly representing summer, fall, and winter seasons. These diagrams have been constructed to show the predominant wind direction and force for each 500-foot level and for as many individual hours during the day as the data allowed.

A 45-degree sector of direction containing the largest number of cases determined the predominant direction and is represented by the arrow. Each wind arrow is labeled to show the total number of observations at that time and level, and the number of observations in which the wind was from the direction shown by the arrow. When another direction was also noted in a large number of observations, a secondary dotted arrow is shown and labeled with the number of cases.

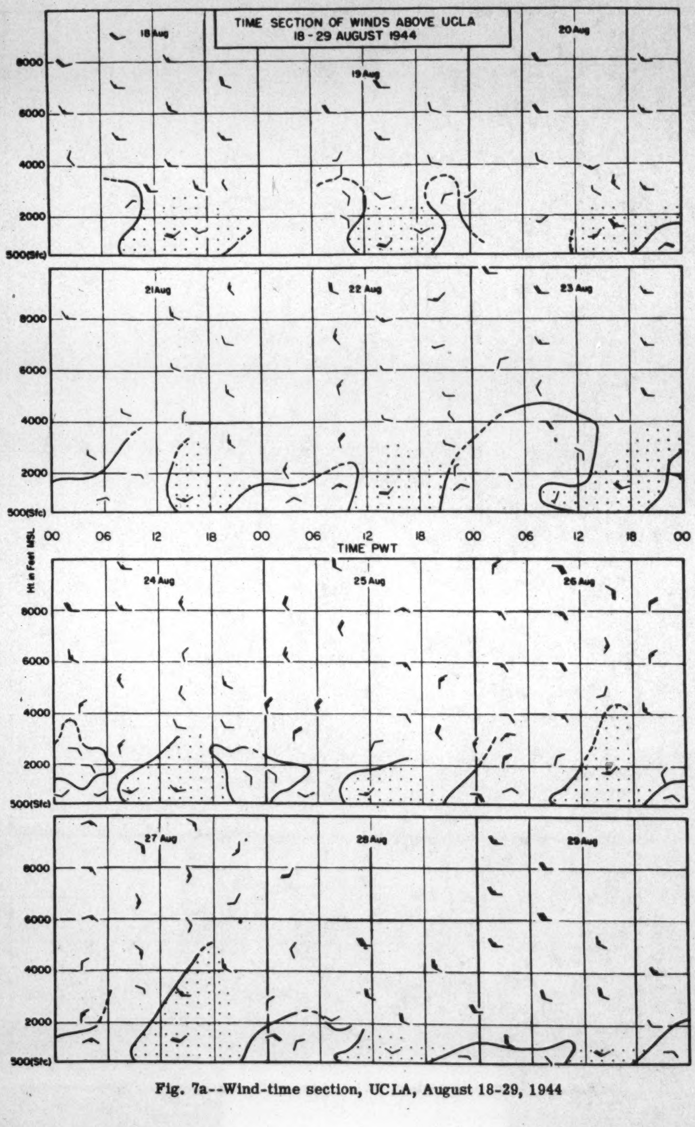

Fig. 7a--Wind-time section, UCLA, August 18-29, 1944

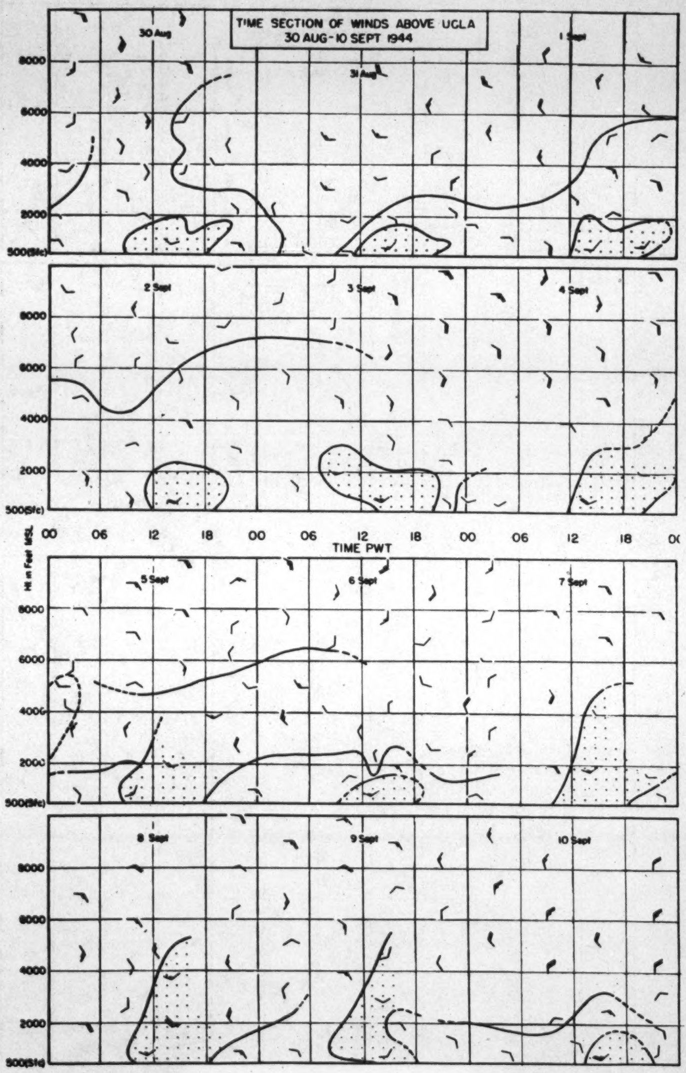

Fig. 7b--Wind-time section, UCLA, August 30 - September 10, 1944

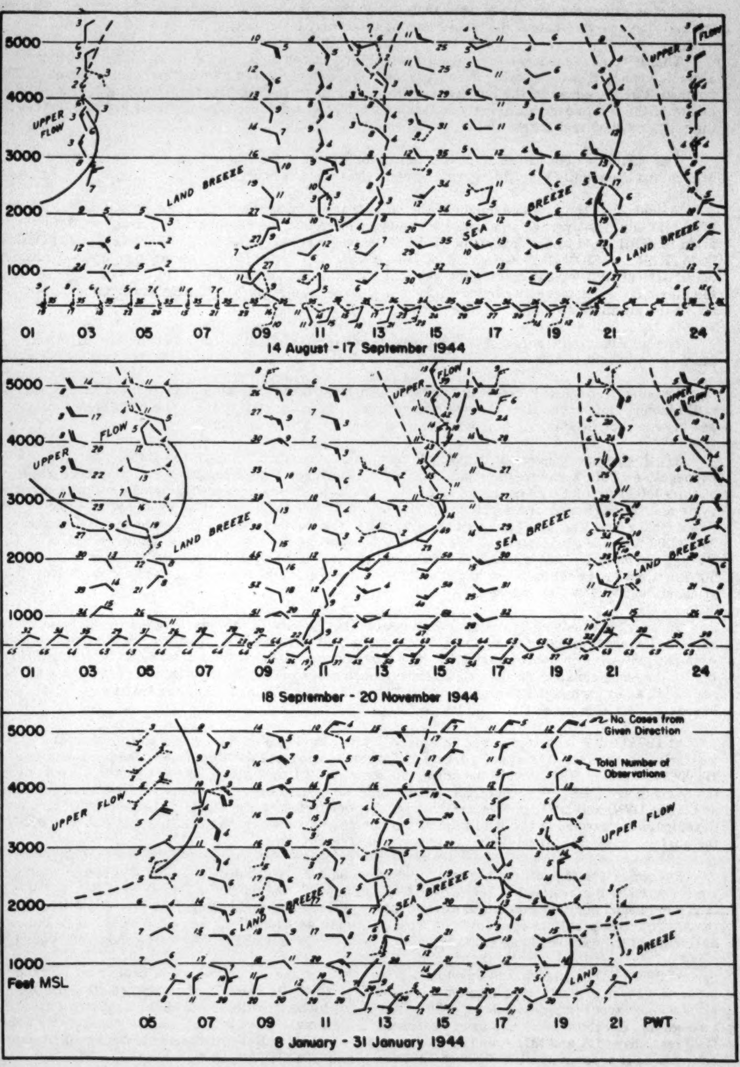

Fig. 8--Predominant daily winds at UCLA

The average time sections have been analyzed in the same manner described previously. On the basis of the analysis comparisons between seasons may be drawn.

The three seasons have several characteristics in common. In the lowest 2000 feet there is a cyclic change from southwest in the afternoon to easterly in the evening and early morning. The southwest sea breeze had the longest duration in summer and the shortest in winter. The total height of the sea breeze apparently exceeds 5000 feet in summer, appears to be about 5000 feet in the fall, and 3500 feet in the winter.

The easterlies constitute a greater duration of time in the lower layers than does the sea breeze and apparently extend to greater height than the sea breeze.

Inasmuch as the average height of the base of the temperature inversion at UCLA was about 1800 feet msl, the average wind time sections indicate that the height of the diurnal wind fluctuation is not limited by the inversion. It has been suggested [UNITED STATES ARMY AIR FORCES, WEATHER DIVISION HEADQUARTERS, 1945 b] that "an inversion of temperature and a decrease of relative humidity characterize the vertical extent of the land breeze." In the Los Angeles basin the diurnal wind changes attributed to the sea-land breeze regime definitely occur considerably above the prominent subsidence inversion.

The maximum velocities of the sea breeze occurred at 1000 to 1500 feet msl at UCLA, the elevation of which is 500 feet.

As noted from the time sections for individual days, the averages show that the land breeze is still blowing aloft at the time the sea breeze begins in the lower layers. The persistence of the sea breeze above the initial land wind is, however, much less distinct.

Areal wind patterns on an individual day--On September 5-6, 1944, the authors enlisted the cooperation of six Army weather stations in the Los Angeles area to observe slow ascent pibals at time intervals of 1-1/2 hours for a 24-hour period. The day chosen was at the end of a stratus cycle and the beginning of a foehn condition caused by the development of high pressures above the Great Basin (see Fig. 4). There were no fronts in the western United States during the period. At 10,000 feet the winds over the area were controlled by the high center in Idaho. At 15^h00^m PWT, September 5, 1944, the thermal low present over the Mojave Desert was well marked at 5000 feet but the resulting west winds at that level were overcome by east winds of the anticyclone at about 09^h00^m PWT on the 6th.

To provide an easier synthesis of the geographic picture of the development of the local wind pattern, the cross-section of Figure 9 is presented. It represents a profile from the coast inland; each station is shown approximately at its perpendicular distance from the coast. Van Nuys (DVN) lies in the San Fernando Valley, which experiences a sea breeze flowing in from the passes to the southeast as explained in the discussion of Figure 5. The distance along the trajectory of the sea breeze was used to place DVN and RV on the profile.

At 18^h00^m PWT on September 5, 1944, all stations shown on the profile were experiencing westerly sea breeze. The upper portion of Figure 9 shows the development of the land wind from 19^h00^m to 01^h00^m. At 19^h00^m the land wind shows only as a shallow layer of easterly winds near the surface at UCLA, DVN, and DUA. At 21^h00^m easterlies occur from the surface up to 1500 feet at UCLA, DVN, and DUA, but westerlies are still occurring at Mines Field (LA) and at DOI. The development eastward of the land wind at the surface as shown by the profiles was checked with the surface winds at stations lying near the cross-section line.

The lower set of profiles in Figure 9 shows a uniformly developing layer of easterly winds, represented by the area below the profile lines of 03^h00^m and 06^h00^m. It will be noted that the land wind began near the coast and worked inland, increasing in depth fastest over the inland stations. The first pibal showing any land wind above Mines Field (LA) was at 03^h00^m. This late beginning of the east winds at LA is typical of the average surface wind regime shown in Figure 5.

At 09^h00^m the land wind is developed at all stations, but LA shows a sea breeze up to 1100 feet and a layer of easterlies between 1100 and 2700 feet. By 13^h00^m westerly sea wind occurs at all stations except the most inland, TUT. Due to the foehn conditions the usual westerly flow through San Gorgonio Pass has been reversed. A thin layer of east winds can be seen at this hour 1500 feet above LA and UCLA and at 3000 feet above DVN, while a considerable thickness of easterlies is still present at DUA (2000 to 4200 feet), and DOI (3500 to above 5000 feet). The fact that the sea breeze at 13^h00^m PWT is thicker at DVN than at DUA is probably explained by the fact that the two stations are not so close together geographically as the profile indicates.

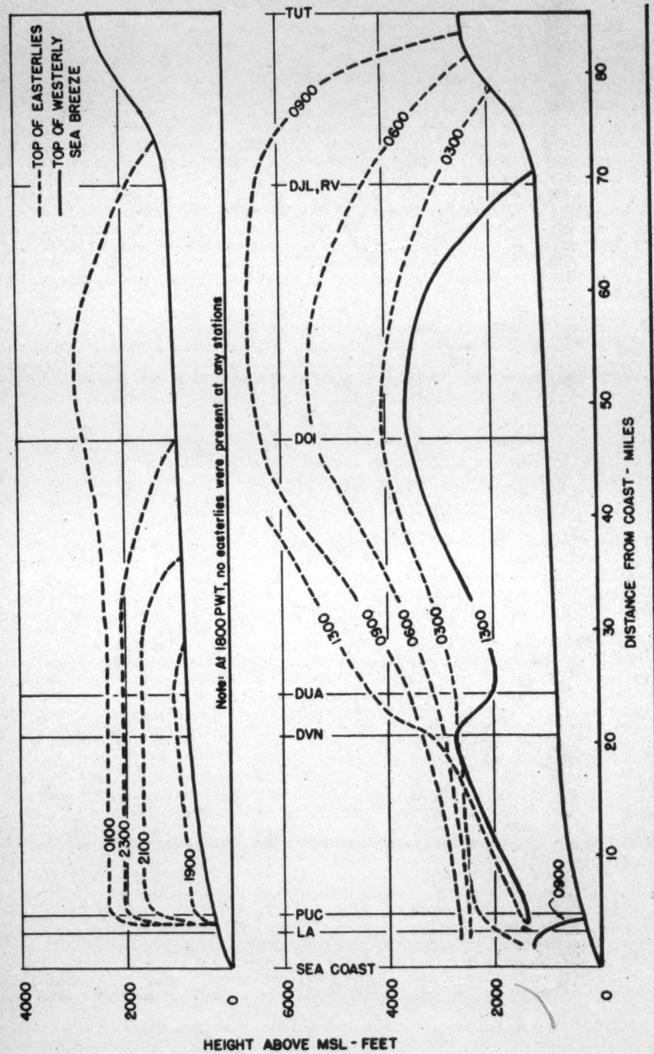

Fig. 9--Profiles of land and sea winds at various hours, Los Angeles basin, September 5-6, 1944

Air pollution and visibility

Visibility is the regularly observed meteorological element most indicative of the amount of air pollution, though it is by no means a perfect index. It will be shown in this section how a knowledge of advection and convection processes can be applied to explain some of the variations of visibility and air pollution over Southern California stations.

Visibility, as determined in the hourly weather observations during the daylight hours, is the maximum distance at which a bulky dark object, such as a water tank, can be seen against a sky background. Night visibility references are usually lights selected to give visibility observations equivalent to those of daytime under the same atmospheric conditions. It is commonly noted that a dark object against a sky background in daytime does not disappear with distance by being blotted out with a darkening screen of intervening atmosphere. Instead, the disappearance is due to progressive brightening of the dark object from black to gray until it finally blends into the distant sky brightness. The paramount control of visibility is thus seen to be the amount of light scattered into the line of sight by small particles in the air, rather than the absorption of light from the object. Some absorption does occur, especially if many of the intervening particles are opaque solids, but this effect is ordinarily negligible in comparison with the glare produced by scattering of the sky light.

Particles which limit the visibility include all types of air pollution as well as naturally-occurring impurities and the air molecules themselves. For the purposes of this paper, all the particles may be classified as follows: (1) Air molecules--nitrogen, oxygen, argon, water vapor, carbon dioxide, and minor gases; (2) hygroscopic nuclei--including both natural materials such as sea salt, and artificial combustion products; and (3) non-hygroscopic particles--including artificial combustion products and natural dust.

The restrictions to visibility recognized in ordinary weather observations are fog, smoke, and haze. "Haze" is a particularly inclusive term. At most weather stations it is used to describe conditions of low visibility which do not appear to fall under the more easily identified conditions of fog or smoke [UNITED STATES DEPARTMENT OF COMMERCE, WEATHER BUREAU, 1941]. Being so vaguely defined, the word haze has been avoided in this paper.

"Smoke" is another word of somewhat variable meaning. British meteorologists apply it only to the non-hygroscopic combustion products. This is not in agreement with the definitions of the United States Weather Bureau, which include odor as a means of identification. Non-hygroscopic smoke particles are usually quite large and when present have pronounced effects on the visibility.

At most stations, however, the chief source of variation in the visibility lies in the hygroscopic nuclei. Thus by studying the visibility changes some insight into the number and characteristics of hygroscopic nuclei present may be obtained. Variation of the visibility is not necessarily associated with changes in the number of nuclei. Hygroscopic nuclei have the property of increasing in size as the relative humidity of the air increases toward 100 per cent. If the relative humidity reaches a certain degree of super-saturation (that is, over 100 per cent) the particles grow rapidly to the size of fog or cloud droplets. Until that critical relative humidity is reached the reduction of visibility is gradual, but it may nevertheless be appreciable.

Observed visibility-relative humidity relations--Figure 10 shows the marked difference between Santa Maria and the Los Angeles basin stations in the visibility-relative humidity relation. The Figure was prepared by determining the mean visibility for five per cent ranges of relative humidity, in a manner similar to that used by WRIGHT [1939]. All hours of the day were included in the averages.

Two periods were studied; the month of August 1944, and October 1 - November 19, 1944. Since the summer weather conditions persisted well into the fall of 1944 the two periods gave similar results. For relative humidities greater than 85 per cent the usual decrease of visibility with increasing relative humidity is observed at all three stations. The presence of pollution effects at UCLA and HB is clearly seen in the diminishing visibility as the relative humidity decreases below 85 per cent. Further studies to determine the effects of hygroscopic nuclei alone might eliminate such variations due to the presence of non-hygroscopic smoke or dust particles.

Diurnal variations--By comparing the diurnal changes in visibility and relative humidity at different stations the relative importance of air impurities and changes in their distribution become apparent. Figure 11a presents the average diurnal variation of visibility and relative

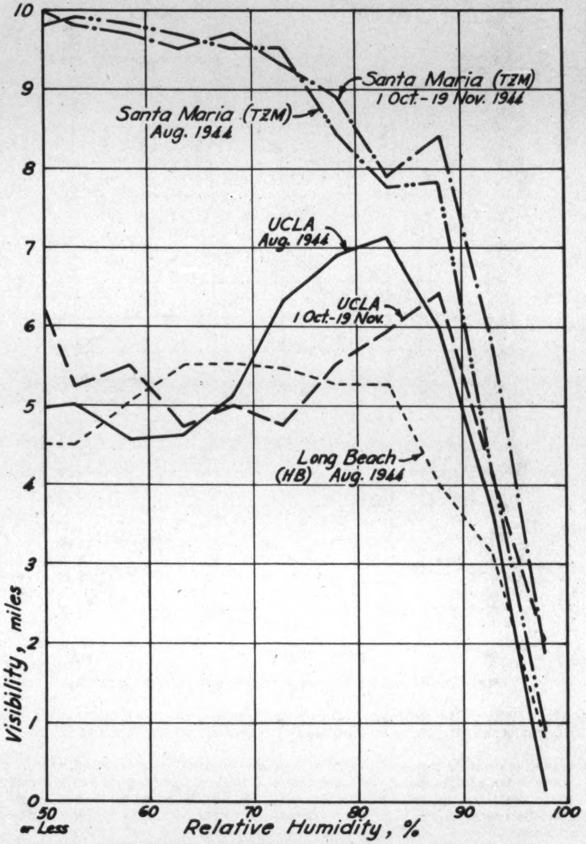

Fig. 10--Variation of visibility with relative humidity

humidity for August 1944 at Santa Maria, UCLA, and Long Beach. While the diurnal change of relative humidity is much the same at all three stations, the variations of visibility show pronounced differences. Most of these may be explained by analysis of the factors acting at the different stations.

At Santa Maria there is a nearly inverse relation between the visibility and relative humidity, as can be seen in the Figure. The surface sea breeze ends at $22^{h}00^{m}$ PWT and a period of calms or light variable winds ensues, continuing through the night. The relative humidity increases slowly from $22^{h}00^{m}$ to $01^{h}30^{m}$, and remains fairly constant thereafter until sunrise. The visibility, however, decreases rather rapidly from $22^{h}00^{m}$ to $01^{h}30^{m}$. This is probably caused by a combination of the rising relative humidity and the cessation of smoke-free advection of the sea breeze, although it cannot be said from these data to what extent each contributes. From $01^{h}30^{m}$

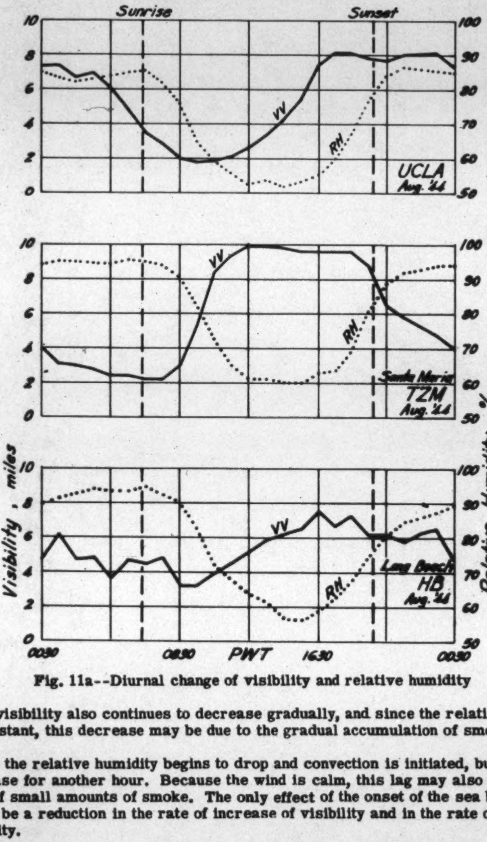

Fig. 11a--Diurnal change of visibility and relative humidity

to sunrise the visibility also continues to decrease gradually, and since the relative humidity is essentially constant, this decrease may be due to the gradual accumulation of smoke.

At sunrise the relative humidity begins to drop and convection is initiated, but the visibility does not increase for another hour. Because the wind is calm, this lag may also be explained by accumulation of small amounts of smoke. The only effect of the onset of the sea breeze at 10^h00^m PWT seems to be a reduction in the rate of increase of visibility and in the rate of decrease of relative humidity.

Thus Santa Maria experiences a sea breeze of long duration each day and no appreciable land breeze at night. The diurnal variation of visibility is almost entirely explained by the diurnal change of relative humidity, although there is evidence of minor smoke accumulation during the calm portion of the night and early morning, which is later blown away by the sea breeze.

At UCLA a northerly land breeze begins at 22^h00^m PWT (see Fig. 5) and continues until 06^h00^m. During this time the relative humidity is nearly constant and the visibility drops, slowly until 03^h30^m, then rapidly. The decrease in visibility must be due to smoke brought in on the land breeze. Because of the lack of smoke sources to the north of UCLA, the northerly mountain wind during the night cannot account for this smoke advection. However, at the foot of the slope the north wind merges into a broad easterly current flowing toward the ocean. Since UCLA is located in the northwestern part of the city, these general east winds of the lower basin tend to cover visibility reference marks south of the station with smoke from the industrial section. The station itself may remain in relatively clear air of the northerly mountain breeze.

The land breeze stops at sunrise and the relative humidity falls rapidly. Calms or very light south-southeast winds are observed until 10^h00^m PWT. The visibility does not improve, however. The conclusion is that smoke or other impurities must be present and persist until 10^h00^m. These particles tend to accumulate in the lowest valleys during the night. In the calm period after sunrise convection currents continue to reduce the visibility by stirring the dense smoke of the lower terrain up to the elevation of the station.

This effect of convection is also shown in Figure 11b, prepared from hourly observations taken during January 1945. The visibility was observed separately in each of the six sectors indicated in the Figure. The nearby Santa Monica Mountains dominate the northwesterly half of the horizon and are practically free of smoke sources. The southeasterly sectors encompass the major smoke sources and low valleys into which smoke tends to settle at night. It is evident that the decrease in visibility shortly after sunrise is more pronounced in the direction of the low valleys. Some of this is, of course, the effect of smoke sources which operate only during the normal business hours each day, but convection is the primary factor in lifting the smoke to the station elevation.

After convection has lifted the smoke to the level of UCLA, continuation of the process tends to mix the smoke particles through a thicker layer. The mixture is thus diluted and the visibility tends to increase. Between 08^h00^m and 10^h00^m this effect, combined with the falling relative humidity, stops the fall of visibility.

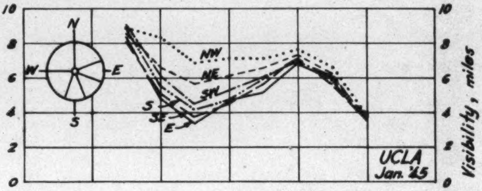

Fig. 11b--Diurnal change of visibility by directions, UCLA

At 10^h00^m PWT the sea breeze begins. The rate of decrease of relative humidity is diminished and the visibility begins to rise. This indicates that the primary effect of onset of the sea breeze is to raise the visibility by carrying away the impurities brought in by the land breeze during the night.

In summary, then, UCLA experiences a pronounced sea- and land-breeze regime. The diurnal variation of visibility is thrown out of its usual relationship with the relative humidity by the presence of appreciable amounts of impurities advected by the land breeze, and also by the diurnal change of convection which affects the stratification of the pollution.

A detailed analysis of the visibility regime at Long Beach (HB) will not be made. From an inspection of the Figure it is apparent that HB has a regime between that of TZM and UCLA. The presence of large amounts of smoke reduces the dependence of visibility on the relative humidity. The low elevation of the station, however, reduces the effect of stratification of the air, since the station is less often completely above the smoke layer. Irregular sources of the impurities advected over the station are indicated by the frequent breaks in the visibility curve.

Conclusions--Certain variations in the visibilities recorded at weather stations in the Los Angeles area indicate the presence of air pollution and its vertical and horizontal distribution. Special observations, supplementing the regular weather records, show the important part played by the changing height of the temperature inversion and by the diurnal wind structure in distributing the contaminated air. It is concluded that a considerable amount of information regarding the type and distribution of air pollution over the city may be obtained by a thorough study of available climatological records, possibly supplemented by a few additional observations of the controlling features. Such studies can yield long-range estimates of the vulnerability of certain locations in the city to low visibility or smoke nuisance. These are of special interest in planning airports and zoning ordinances, and should be considered in all phases of community planning.

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Service Technical Report 105-1, "The structure of the local winds in the Los Angeles basin, California," September 1945, and "The diurnal wind regime in relation to coastal weather," unpublished.

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COMPUTATION OF VERTICAL MAGNETIC ANOMALIES FROM TOTAL MAGNETIC FIELD MEASUREMENTS

D. S. Hughes and W. L. Pondrom

Abstract--Magnetic measurements for geophysical work have been largely confined to measurement of the vertical field. Recently an instrument that measures only the total magnetic field has been invented and used with considerable success. Its operation is simpler and faster than the vertical magnetometer and its accuracy is as good as the best of the available vertical instuments. Since the instrument responds only to the total field, its readings are completely independent of orientation or leveling. It is shown that the readings of this instrument give the component of the magnetic anomalies along the direction of dip of the Earth's field. Since this "slant" anomaly is not directly comparable with ordinary measurements of the vertical and horizontal anomalies, or easily interpretable, a method of computing the equivalent vertical and horizontal anomalies has been devised. It is shown that the horizontal and vertical anomalies can be expressed as surface integrals over the surface of measurement of the "slant" anomaly. Means of evaluating these integrals are discussed.

Magnetic measurements for geophysical work have been largely confined to measurement of the vertical field; only a small amount of work has been done with the horizontal field. This preference arises from the fact that not only is the vertical magnetometer simpler in operation but maps of the vertical component are usually more easily interpreted.

Recently an instrument that measures only the total magnetic field has been invented and used with considerable success. Its operation is simpler and faster than that of the vertical magnetometer and its accuracy is as good as that of the best of the available vertical instruments.

Assume that in a given area the magnetic field can be divided into two parts; first, that caused by the Earth as a whole considered in its large scale aspect; and second, that caused by local geologic structure. In regions not containing large deposits of ferro-magnetic materials, the Earth's field will be very much greater than that arising from local structure. Let H be the total field intensity caused by the Earth as a whole, and let ϕ be its angle of dip. Also let H_x be the north component, H_y the east component and H_z the vertical component of the anomalous field caused by local structure in which by north we mean the magnetic north of the Earth as a whole. The components of the total field (Earth as a whole and local structure combined) are then

$$\left.\begin{aligned} T_n &= H_x + H\cos\phi \\ T_e &= H_y \\ T_v &= H_z + H\sin\phi \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and the total field, T, is given by

$$T^2 = T_n^2 + T_e^2 + T_v^2 = H^2 + 2H(H_x\cos\phi + H_z\sin\phi) + H_x^2 + H_y^2 + H_z^2 \ldots\ldots\ldots (2)$$

It is this quantity, T, that the new instrument measures. Equation (2) may be rewritten as

$$H_x\cos\phi + H_z\sin\phi = (T^2 - H^2)/2H - (H_x^2 + H_y^2 + H_z^2)/2H \ldots\ldots\ldots\ldots (3)$$

This may be further rewritten as:

$$H_x\cos\phi + H_z\sin\phi = T - H - [H_x^2 + H_y^2 + H_z^2 - (T - H)^2]/2H \ldots\ldots\ldots\ldots (4)$$

Since

$$0 \leq (T - H)^2 \leq H_x^2 + H_y^2 + H_z^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

and H is of the order of 60,000 to 80,000 g and the total anomalous field will be of the order of several

hundred (or less), the error in neglecting the bracketed second term of (4) will be at most one or two g and will usually be much smaller than this amount. Correction for this error can be accomplished by an iteration process to be discussed later. It should be observed at this point that the neglected term will never change sign.

The left hand side of (4) is the component of the anomalous field in the direction of the dip of the field of the Earth considered as a whole. Thus N represents this component,

$$N = H_x \cos\phi + H_z \sin\phi \doteq T - H \quad \ldots\ldots (6)$$

Now in dealing with an area of a few hundred square miles, the most practical thing to do is to choose H to be a constant and equal to the average over the area of the observed total field, T. Let $\overline{T}$ be this average. Then we have

$$N = T - \overline{T} \quad \ldots\ldots (7)$$

Thus the readings of the new instrument can be reduced in a simple fashion to the component of a local field in the direction of the dip of the field of the Earth as a whole.

For many purposes this slant anomaly, N, is probably satisfactory, but it is inconvenient for many analytical interpretation procedures, and it is difficult to correlate N to any existing maps of the vertical anomaly. It is important to discover a method of computing the vertical anomaly from the observed values of N, the slant anomaly. It is easily shown that this is possible, and although the derivations of the necessary formulae are somewhat complex, the final numerical computation that must be carried out on the maps is about the same complexity as that required in making topographic correction in gravity work.

Take the surface of the Earth as the xy- plane with the x- axis directed toward the north and the z- axis directed upward. All of the singularities of the anomalous field are below the xy- plane, or in other words in the region $z < 0$. The most general solution of the Laplace equation valid in the region $z \geq 0$ under this condition may be taken in the form of

$$V(x,y,z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{(-z\sqrt{\lambda^2+\mu^2} + i\lambda x + i\mu y)} F(\lambda,\mu)\,d\lambda\,d\mu \quad \ldots\ldots (8)$$

The function $F(\lambda,\mu)$ must obviously be such that the integral exists but is otherwise determinable only in terms of boundary conditions upon the potential function $V(x,y,z)$.

Assuming suitable convergence, the field quantities $H_x = \partial v/\partial x$ and $H_z = \partial v/\partial z$ may be computed by differentiation under the integral sign in (8) to give:

$$\left.\begin{aligned} H_x(x,y,z) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{(-z\sqrt{\lambda^2+\mu^2} + i\lambda x + i\mu y)} (i\lambda) F(\lambda,\mu)\,d\lambda\,d\mu \\ H_z(x,y,z) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{(-z\sqrt{\lambda^2+\mu^2} + i\lambda x + i\mu y)} (-\sqrt{\lambda^2+\mu^2}) F(\lambda,\mu)\,d\lambda\,d\mu \end{aligned}\right\} \ldots (9)$$

Hence from (6) and (9)

$$N(x,y,z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{(-z\sqrt{\lambda^2+\mu^2} + i\lambda x + i\mu y)} (i\lambda\cos\phi - \sin\phi\sqrt{\lambda^2+\mu^2}) F(\lambda,\mu)\,d\lambda\,d\mu \quad (10)$$

and for $z = 0$ we have

$$N(x,y,z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{(i\lambda x + i\mu y)} (i\lambda\cos\phi - \sin\phi\sqrt{\lambda^2+\mu^2}) F(\lambda,\mu)\,d\lambda\,d\mu \quad \ldots . (11)$$

Now $N(x,y,0)$ is known from the application of (6) to the experimental observations. This integral, (11), is of the well-known double Fourier integral type. Assuming a knowledge of $N(x,y,0)$ over the entire xy-plane (11) is readily solved by the usual Fourier integral methods for the case of constant ϕ, to give

$$(i\lambda\cos\phi - \sin\phi\sqrt{\lambda^2+\mu^2}) F(\lambda,\mu) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0) e^{-i(\xi\lambda+\eta\mu)}\,d\xi\,d\eta \quad \ldots\ldots (12)$$

Substituting the value of $F(\lambda,\mu)$ obtained from (12) into (8) and reversing the order of integration we obtain

$$V(x,y,z) = \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\left[\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{e^{\left\{-z\sqrt{\lambda^2+\mu^2}+i\lambda(x-\xi)+i\mu(y-\eta)\right\}}}{i\cos\phi\,\lambda - \sin\phi\sqrt{\lambda^2+\mu^2}}\,d\lambda d\mu\right]d\xi d\eta \quad \ldots\ldots\ (13)$$

Now define $I(u,v,w)$ by

$$I(u,v,w) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{e^{\left\{-w\sqrt{\lambda^2+\mu^2}+i\lambda\mu+i\mu v\right\}}}{i\cos\phi\,\lambda - \sin\phi\sqrt{\lambda^2+\mu^2}}\,d\lambda d\mu \quad \ldots\ldots\ (14)$$

where u, v and w are real and $w > 0$ and in this integral make the coordinate transformation to the variables ρ and θ defined by

$$\lambda = \rho\cos\theta \qquad \mu = \rho\sin\theta$$

Equation (14) then becomes

$$I(u,v,w) = \frac{1}{2\pi}\int_0^{2\pi}\int_0^{\infty} \frac{e^{-\rho(w - iu\cos\theta - v\sin\theta)}}{i\cos\phi\cos\theta - \sin\phi}\,d\rho d\theta$$

Integrating with respect to ρ, this reduces to

$$I(u,v,w) = \frac{1}{2\pi}\int_0^{2\pi}[1/(w - iu\cos\theta - iv\sin\theta)(i\cos\phi\cos\theta - \sin\phi)]d\theta$$

which may be evaluated by means of contour integration.

In this integral set $q = e^{i\theta}$, then

$$I(u,v,w) = (1/2\pi i)\oint 4q/[q^2(u-iv) + 2iqw + (u-iv)](q^2\cos\phi + 2iq\sin\phi + \cos\phi)dq$$

where the contour of integration is the unit circle with center at the origin, and is described in the counter-clock-wise sense. The denominator has four simple zeros in the complex plane at the points

$$q_1 = -i(\sin\phi + 1)/\cos\phi \qquad q_2 = -i(\sin\phi - 1)/\cos\phi$$

$$q_3 = -i(w + \sqrt{u^2+v^2+w^2})/(u-iv) \qquad q_4 = -i(w - \sqrt{u^2+v^2+w^2})/(u-iv)$$

If $w > 0$ and $0 < \phi < \pi$, only two of these roots, q_2 and q_4, will lie inside the contour of integration. Computing the residues at these two roots

$$I(u,v,w) = \frac{-\cos\phi\,(w\cos\phi - u\sin\phi) - iv\cos\phi}{v^2 + (w\cos\phi - u\sin\phi)^2} - \frac{1}{\sqrt{u^2+v^2+w^2}}\times$$

$$\frac{\sin\phi\,(u^2+v^2) - uw\cos\phi - iv\cos\phi\sqrt{u^2+v^2+w^2}}{v^2 + (w\cos\phi - u\sin\phi)^2} =$$

$$-\frac{\sin\phi\sqrt{u^2+v^2+w^2} + w}{\sqrt{u^2+v^2+w^2}\,(\sqrt{u^2+v^2+w^2} + w\sin\phi + u\cos\phi)} \quad \ldots\ldots\ (15)$$

From equations (13), (14), and (15) it is obvious that

$$V(x,y,z) = -\frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\,\frac{R\sin\phi + z}{R[R + z\sin\phi + (x-\xi)\cos\phi]} \quad \ldots\ldots\ldots(16)$$

is a formal expression for the required potential function where

$$R = \sqrt{(x-\xi)^2 + (y-\eta)^2 + z^2}$$

It gives the potential in the upper half-space $z \geq 0$ in terms of the values of $N(\xi,\eta,0)$ the component of the anomalous field in the direction of the dip at $z = 0$. The angle ϕ determining this direction has been assumed constant. If this restriction is removed the solution of the problem is not obtainable by the analytical methods employed here.

The components of the field are readily found by differentiation to be

$$H_x(x,y,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\times$$

$$\left\{\frac{\sin\phi\,[(x-\xi) + R\cos\phi]}{R[R + z\sin\phi + (x-\xi)\cos\phi]^2} + \frac{(x-\xi)z\,[2R + z\sin\phi + (x-\xi)\cos\phi]}{R^3[R + z\sin\phi + (x-\xi)\cos\phi]^2}\right\} d\xi d\eta \quad \ldots(17)$$

$$H_y(x,y,z) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\times$$

$$\left\{\frac{\sin\phi\,(y-\eta)}{R[R + z\sin\phi + (x-\xi)\cos\phi]^2} + \frac{(y-\eta)z\,[2R + z\sin\phi + (x-\xi)\cos\phi]}{R^3[R + z\sin\phi + (x-\xi)\cos\phi]^2}\right\} d\xi d\eta \quad \ldots(18)$$

$$H_z(x,y,z) = -\cot\phi\, H_x(x,y,z) + \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{N(\xi,\eta,0)\,z}{\sin\phi\, R^3}\, d\xi d\eta \quad \ldots\ldots\ldots(19)$$

For the components on the plane $z = 0$, we find by evaluating the limit as $z \to 0$

$$H_x(x,y,0) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\left\{\frac{\sin\phi\,[(x-\xi) + \rho\cos\phi]}{\rho[\rho + (x-\xi)\cos\phi]^2}\right\} d\xi d\eta \quad \ldots\ldots\ldots(20)$$

$$H_y(x,y,0) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\left\{\frac{\sin\phi\,(y-\eta)}{\rho[\rho + (x-\xi)\cos\phi]^2}\right\} d\xi d\eta \quad \ldots\ldots\ldots(21)$$

$$H_z(x,y,0) = -\cot\phi\, H_x(x,y,0) + N(x,y,0)/\sin\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots(22)$$

or

$$H_z(x,y,0) = \frac{N(x,y,0)}{\sin\phi} - \frac{\cos\phi}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\;\frac{[(x-\xi) + \rho\cos\phi]}{\rho[\rho + (x-\xi)\cos\phi]^2}\; d\xi d\eta \quad \ldots\ldots(23)$$

where

$$\rho = \sqrt{(x-\xi)^2 + (y-\eta)^2}$$

Since the origin may be any point in the xy-plane, there is no loss in generality in taking $x = y = 0$ in (23) and we have

$$H_z(0,0,0) = \frac{N(0,0,0)}{\sin\phi} - \frac{\cos\phi}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} N(\xi,\eta,0)\left\{\frac{-\xi + \cos\phi\sqrt{\xi^2+\eta^2}}{\sqrt{\xi^2+\eta^2}\,(\sqrt{\xi^2+\eta^2} - \xi\cos\phi)^2}\right\} d\xi d\eta \quad \ldots(24)$$

Changing to the polar coordinates, $\xi = r \cos\theta$ and $\eta = r \sin\theta$, (24) becomes

$$H_z(0) = \frac{N(0)}{\sin\phi} + \frac{\cos\phi}{2\pi}\int_0^{\infty}\int_0^{2\pi}\frac{N(r,\theta)}{r}\left\{\frac{\cos\theta - \cos\phi}{(1-\cos\phi\cos\theta)^2}\right\} dr\,d\theta \quad \ldots\ldots (25)$$

or

$$H_z(0) = \frac{N(0)}{\sin\phi} + \frac{1}{2\pi}\int_0^{\infty}\int_0^{2\pi}\frac{N(r,\theta)}{r}\frac{\partial}{\partial\theta}\left\{\frac{\cos\phi\sin\theta}{1-\cos\phi\cos\theta}\right\} dr\,d\theta \quad \ldots\ldots\ldots (26)$$

With the values of H_x, H_y and H_z computed from equations (20), (21), and (23), the error introduced by neglecting the last term (4) may be estimated, and if desirable may be corrected by an iteration process. In general, this error will be negligible, and for the most part only H_z will be computed, (25) or (26).

These integrals have a pole at the origin and do not exist unless the function $N(r\theta)$ is expandable in a power series in the neighborhood of the origin; this condition is always satisfied by $N(r\theta)$.

For actual numerical evaluation of H_z several schemes may be utilized. The most convenient appears to be a variety of zone plate such as that used in computing topographic corrections.

The zone plate is formed by circles of radius $r, r_2, \ldots r_n$ and then divided by radial lines into compartments. In each compartment $N(r\theta)$ may be assumed constant. The zone containing the origin is not divided and the integral over it will then be zero.

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INCREASE IN THE PERIOD OF WAVES TRAVELING OVER LARGE DISTANCES: WITH APPLICATIONS TO TSUNAMIS, SWELL, AND SEISMIC SURFACE WAVES

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Abstract--An expression is derived from very general assumptions for the increase in wave period during long-distance propagation. To illustrate the general nature of the solution, application is made to three different geophysical phenomena: First, to the tsunami from the Aleutian earthquake of April 1, 1946; second, to the long forerunners of the swell recorded at the wave station in Pendeen, England; and finally to the seismic surface waves from the Montana earthquake of June 28, 1925, and a smaller Mexican shock in 1943. In the case of the tsunami and the swell, observations and theory are in good agreement. For the seismic surface waves the theory gives at least the right order of magnitude. Application of the theory to the period increase of swell seems furthermore to provide a simple, rational basis for locating and tracking storms at sea by means of swell observations, and may therefore be of interest in weather forecasting.

Introduction--Changes in wave period have been noticed for many types of wave propagation. GUTENBERG [see "References" at end of paper, 1929] has summarized some of the observations and gives as examples the propagation of swell, microseisms, ordinary seismic waves, and sound waves from explosions. Changes in wave period appear to be truly geophysical phenomena, noticeable only when dealing with waves traveling for long times over long distances.

The present paper attempts to explain these changes as the consequence of wave dispersion, that is, as the result of the dependence of wave velocity upon wave period. The only assumptions that must be made are that (1) individual waves maintain their identity, and (2) at some given time the wave period changes with distance. Under these conditions it is shown that dispersion must lead to an increase in period of an individual wave. Although the concepts of "dispersion" and "period increase" have been previously connected by several authors, they seem not to have noted this effect upon individual waves, and for that reason have sought explanation in internal friction rather than dispersion [RICHTER, 1943].

The effect of dispersion on wave period is first considered from a qualitative point of view. The rate of period increase is then derived quantitatively in very general terms from the assumption that the wave crests maintain their identity. The solutions are applied to three specific problems for which they can be checked by observations.

The first application deals with tsunamis, a type of wave motion not ordinarily considered dispersive. However, a slight dependence of the velocity upon period suffices to bring about measurable changes in period over long distances, and the observed changes can be brought into accord with theory. A method is suggested whereby the nature and size of the original disturbance may be estimated from the tidal record at any given station.

The second application deals with long, low waves which appear to precede the visible swell from a storm. These forerunners of the swell, which have been recorded at newly established wave stations at Pendeen, England, and Woods Hole, Massachusetts, obey the general dispersion law. The theory can also be applied to trace storms across the ocean by means of these wave records. The computed path of two actual storms is shown to be in good agreement with the observations on weather maps. The application towards a practical system of storm warning is briefly discussed.

The third application deals with seismic surface waves. Good records from a large number of seismograph stations make it possible to measure the period changes with somewhat greater precision than for tsunamis and swell, but this advantage is more than offset by the lack of a dependable analytic expression for dispersion. The relationship between velocity and period has to be found from observations, and these give only a very approximate answer. Within the limitations thus imposed, theory and observations of the period increase of seismic surface waves are consistent.

The principles can also be applied to other types of wave motion, indeed to any wave motion for which individual waves maintain their identity and for which the velocity depends to any degree, no matter how slight, upon wave period. Observed changes in period may offer a powerful tool for computing the dependence of wave velocity upon period and thereby describing some of the characteristics of the transmitting medium. The wide applicability derives from the general nature of the basic equation, to which Rossby has applied the descriptive term "wave equation of continuity."

Only the kinematics of wave motion will be considered, that is, no attention will be paid to problems involving wave height. The relationships between group velocity, phase velocity, and energy propagation have been investigated in a fundamental paper by ROSSBY [1945] to which we shall make frequent reference.

Nature of the period increase--A number of attempts have been made to explain the increase in wave period in terms of a shift in spectrum brought about by viscosity. This point of view has been summarized by RICHTER [1943] (underscore mine): "Some extension of theory is required to account for the frequent observation that the prevailing periods of all types of seismic waves increase with distance. This cannot wholly be due to the normal spreading of an impulsive disturbance with filtering out of the shorter periods. . . . Surface waves show dispersion, the theory showing that velocity should vary with period; *but this cannot account for the increase with distance of the period of a clearly identifiable wave group*. . . . The required effect will be given by some type of viscosity, or internal friction."

The reason why this approach has not led to tangible results lies perhaps in a misunderstanding regarding the true significance of the period spectrum for an impulsively generated disturbance. The shift of this spectrum has, in general, nothing to do with viscosity, and, furthermore, does not relate to the changes of the recorded wave period except through a series of very complex mathematical manipulations. The misunderstanding can be avoided by referring directly to the classical investigations by Cauchy and Poisson [LAMB, 1932, pp. 384-394] on waves produced by a local surface disturbance in deep water.

For an initial displacement of the free surface, which at the time $t = 0$ is assumed to be confined to the immediate neighborhood of the origin $x = 0$, the disturbance of the sea surface at any time t and distance x is given by the Fourier integral $\eta(x, t) = (8\pi/g) \int_\infty^0 (1/T_c^3) \cos (4\pi^2 x/gT_c^2) \times \cos (2\pi t/T_c) dT_c$. The symbol T_c denotes the period of the underlying spectrum. By means of several ingenious approximations the foregoing integral has been evaluated; $\eta(x, t) = (t/2) \sqrt{g/\pi x^3} \times \cos (gt^2/4x - \pi/4)$, provided gt^2 is large compared to x. In regions where this formula holds, changes in height and period from wave to wave are very gradual. For a fixed value of x a wave crest passes at a time t_1, if $gt_1^2/4x - \pi/4 = 2\pi n$, and the following crest at a time t_2, if $gt_2^2/4x - \pi/4 = 2\pi(n + 1)$, where n is any integer. Let T_r, the recorded wave period, be defined as the time interval between successive maxima (or minima) at a fixed point. It follows that $T_r \equiv t_2 - t_1 = 4\pi x/g\bar{t}$, where $\bar{t}$ is the mean of t_1 and t_2.

This very brief review of the classical method should serve to point out the difference between the period T_c of the underlying spectrum, and the period T_r of the recorded waves. Accordingly we shall speak of component periods and recorded periods. It is important to note that the underlying wave system is not in any simple manner discernible in the recorded waves, and may indeed be regarded as a mathematical abstraction.

It is not proper to speak of an increase in the component periods, since all periods between zero and infinity are assumed to be present at all times in the Fourier integral expression. However, different component periods are associated with variable amounts of energy. At first much of the energy is concentrated in the shorter component periods, but a gradual shift takes place toward the longer component periods. This shift follows directly from the dynamics of the problem, and does not involve, as is frequently supposed, the higher attenuation of short component periods. Furthermore, a knowledge of this energy shift, and of the selective attenuation if the latter is important enough to be included, does not offer any direct evidence concerning an increase in the recorded periods. But by dealing directly with the recorded wave periods an increase in period can be explained by the following elementary reasoning.

A group of n waves arrives at station A. The first crest passes at a time $t = 0$, succeeding crests at diminishing intervals $T_1, T_2, \ldots T_n$. This is typical of wave systems generated impulsively. Assume that the recorded period T_r at A decreases linearly with time according to the equation $T_r = T_1 - mt$. The upper portion of Figure 1 shows such a wave system for a constant amplitude. The record is assumed to move from left to right, so that t increases from right to left.

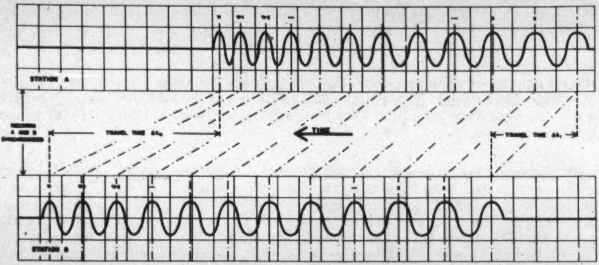

Fig. 1--Schematic presentation of an increase in wave period between stations A and B, showing excess in velocity of longer waves over velocity of shorter waves, causing stretching of entire wave group

Assume, furthermore, that the propagation is dispersive; for this simple illustration let the wave velocity C be proportional to the recorded period; $C = pT_r$.

The first wave has the longest recorded period and the greatest velocity. It will travel over a small distance X between stations A and B in a short time interval, $\Delta t_1 = X/C_1 = X/pT_1$. The last wave, which arrives at A at the time t_n, travels much slower and will take a time interval $\Delta t_n = X/C_n = X/p(T_1 - mt_n)$ to travel from A to B. In Figure 1, $T_n = T_1/2$, and therefore $\Delta t_n = 2\Delta t_1$. The duration of the record at B will exceed the duration at A by $\Delta t_n - \Delta t_1$. Since the number of waves in the record is the same, the average increase in the recorded period equals $(\Delta t_n - \Delta t_1)/n$.

The foregoing discussion would have been more accurate if C_i in the expression for Δt_i had not been computed from the period T_i at station A, but the mean period of the ith wave between stations A and B. But even without the precise differential formulation which follows in the next section, the above considerations show that the wave group "stretches." The result is not merely a shift in spectrum from short to long periods; it is an actual increase of the average recorded period of the waves in the group, and of all individual waves comprising the group.

The formulation of the problem depends therefore upon whether one deals directly with the physical deformations of the transmitting medium, such as we have done, or whether one considers a spectrum of underlying constant-period wave systems, as in the Cauchy and Poisson analyses. In the first case one deals with the recorded period, representing the time interval between two successive maxima (or minima) at a fixed point; in the second case one deals with component periods which are found by generalizing a given portion of a record into a Fourier integral. In the first case wave periods increase, in the second case they remain constant.

For a complete solution, involving wave height as well as wave period, one must follow the method of Cauchy and Poisson. The problem in its simplest two-dimensional form is not an easy one, and attempts to extend the investigation to the case of a finite initial disturbance [BURNSIDE, 1888] or finite depth [PIDDUCK, 1912] have met with great difficulties. By dealing directly with the recorded deformations, without recourse to any underlying spectrum, certain problems can be treated which are too complicated for a complete analysis of the Cauchy-Poisson type. ("In any other problem of wave motion in a dispersive medium we can do little more than argue by analogy to the special problem of waves in deep water . . . " [LOVE, 1911].) The method permits the computation of the period increase for individual waves. Good agreement between the computed and observed values offers strong evidence that the phenomenon is inherent in the kinematics of wave motion, and is not related to the viscous properties of the transmitting medium. The following section is devoted to a mathematical formulation of these principles.

Derivation of the basic equations

Changes in wave length--The wave length, L, of a wave traveling with phase velocity C along the positive x axis changes at the rate

$$\frac{dL}{dt} = \frac{\partial L}{\partial t} + \frac{\partial L}{\partial x}C \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

This change can also be found from the rate at which the wave "stretches" due to the difference in velocity of two adjoining crests:

$$\frac{dL}{dt} = \frac{\partial C}{\partial x}L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Eliminating the total derivative between (1) and (2) gives the following important relationship:

$$\frac{\partial L}{\partial t} + \frac{\partial L}{\partial x}C = \frac{\partial C}{\partial x}L \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

We shall be concerned in general with the case where the wave velocity depends on wave length L and depth h only, or

$$C = C(L, h) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where $L = L(x, t)$, and the bottom profile along the path of travel is given by $h = h(x)$.

Substituting the identity

$$\partial C/\partial x = (\partial C/\partial L)(\partial L/\partial x) + (\partial C/\partial h)(dh/dx) \quad \ldots\ldots\ldots\ldots (5)$$

into (3) gives

$$\partial L/\partial t + [C - L(\partial C/\partial L)]\,\partial L/\partial x = (\partial C/\partial h)(dh/dx)L \quad \ldots\ldots\ldots\ldots (6)$$

If V_L is defined by the equation

$$\partial L/\partial t + (\partial L/\partial x)V_L = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

then to an observer traveling at velocity V_L the wave length remains constant. According to (6) and (7)

$$V_L = C - L(\partial C/\partial L) - L(dh/dx)[(\partial C/\partial h)/(\partial L/\partial x)] \quad \ldots\ldots\ldots\ldots (8)$$

For the special case of constant depth, $dh/dx = 0$, and the partial derivative can be replaced by a total derivative

$$V_L' = C - L(dC/dL) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The V has been primed to denote the case of constant depth.

Equation (9) represents the well-known equation for group velocity at constant depth, and for this special case has been derived by LAMB [1932, pp. 384-394] in a somewhat similar manner. ROSSBY [1945] derives (9) by equating the rate of increase of wave crests within a certain distance Δx to the excess of waves entering at x over those leaving at $x + \Delta x$. In analogy with the problem in hydrodynamics he uses the very descriptive term "wave continuity equation." Rossby also generalizes (9) to include some of our results.

These derivations identify the physical meaning of the term group velocity with the velocity of the locus of a point in whose immediate vicinity the wave length remains constant. The same equation is usually derived from the interference pattern between two wave systems of equal amplitude and slightly different wave length, but that approach is unnecessarily restricted. The only assumption which has been made here is that the waves are "conservative," that is, that individual crests maintain their identity.

Changes in wave period--Wave length, velocity, and period are related by the identity

$$L = CT \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

which permits restating the fundamental law (3) in terms of T and C rather than L and C:

$$C(\partial T/\partial t) + T(\partial C/\partial t) + [C(\partial T/\partial x) + T(\partial C/\partial x)]C = (\partial C/\partial x)CT$$

or

$$\partial T/\partial t + (T/C)(\partial C/\partial t) + C(\partial T/\partial x) = 0 \quad \ldots\ldots\ldots\ldots (11)$$

For the general case assume, as before

$$C = C(T, h), \quad h = h(x) \tag{12}$$

Therefore, $\partial C/\partial t = (\partial C/\partial T)(\partial T/\partial t)$, and (11) becomes

$$\partial T/\partial t + \left\{ C/[1 + (T/C)(\partial C/\partial T)] \right\} (\partial T/\partial x) = 0 \tag{13}$$

To an observer traveling at a velocity

$$V_T = C/[1 + (T/C)(\partial C/\partial T)] \tag{14}$$

the wave period remains constant. It is remarkable that the bottom slope does not enter explicitly into the expression for V_T as it did for V_L, so that, in general, $V_T \neq V_L$. It is simpler to deal with wave period than wave length, because then the equations are the same for the cases of constant and variable depth, or, by our previous notation

$$V_T' = V_T = V_L' \tag{15}$$

In all subsequent equations V_T will be denoted simply by V and referred to as the group velocity.

The wave period of any system of waves in which the crests retain their identity must satisfy the "equation of continuity" (13). Writing this equation in the abbreviated form

$$\partial T/\partial t + V(\partial T/\partial x) = 0 \tag{16}$$

its solution can be put down at once:

$$T = T[t - \int (1/V)dx] \tag{17}$$

It is not possible to solve for the period explicitly, at least not in the general case, since T is contained in V and thus appears on both sides of the equation. As far as the integration is concerned, on the other hand, V can be considered a function of h, or of x only, and

$$\partial T/\partial t = \partial T/\left\{ \partial [t - \int (1/V)dx] \right\} \qquad (\partial T/\partial x) = \partial T/\left\{ \partial [t - \int (1/V)dx] \right\} (-1/V) \tag{18}$$

It can be seen that (17) satisfies the differential equation (16). The limits of integration in (17) are undetermined as yet, because no provisions have been made to fix the coordinate system. In most cases it is convenient to let t = 0, x = 0, designate the time and position of the initial wave generation. If it were possible to measure a period T_0 at or very near the origin, then according to the foregoing convention $T_0 = T(0)$.

Equations (16) and (17) define the "field" of wave period in the xt plane, and will be called *field equations*. By applying the field solution (17) to problems dealing with tsunamis and swell severe restrictions are imposed upon the dependence of period on distance x and time t. It will be shown that these restrictions lead to results in agreement with observations.

In many problems it is more convenient to express the relationships in terms of individual waves. For each individual wave the "travel-time" curve, $x = x(t)$, is fixed, and the transformation from the field equations to the individual wave equation requires a line integral in the xt plane.

Equations for individual waves--To derive changes in period for individual waves, (16) can be combined with either of the equations

$$dT/dt = \partial T/\partial t + (\partial T/\partial x)C \qquad dT/dx = \partial T/\partial x + (\partial T/\partial t)(1/C) \tag{19}$$

to give the following sets of relationships:

$$\frac{dT}{dt} = -\left(\frac{C}{V} - 1\right)\frac{\partial T}{\partial t} = (C - V)\frac{\partial T}{\partial x} \tag{20 a, b}$$

$$\frac{dT}{dx} = -\left(\frac{1}{V} - \frac{1}{C}\right)\frac{\partial T}{\partial t} = \left(1 - \frac{V}{C}\right)\frac{\partial T}{\partial x} \tag{21 a, b}$$

The significance of the total and partial derivatives must be kept in mind: The partial derivatives refer either to changes with distance at a given instant, $\partial T/\partial x$; or changes with time at a given location, $\partial T/\partial t$. The variables x and t are independent.

The total derivatives refer to changes of an individual wave which has traveled a distance x in a time t since it has been generated. For individual waves x and t are not independent. Indeed they are related by (12) and (17):

$$C = C(T, x) = C(x, t) \qquad (22)$$

which together with the definition of wave velocity

$$C = dx/dt \qquad (23)$$

make solutions of the type $t = t(x)$ possible.

This distance-travel relationship for individual waves can in turn be substituted into (17) to give solutions of the form

$$T = T(x) \text{ or } T = T(t) \qquad (24)$$

Equations (20) and (21) give the differential expression, (24) the integral expression, for the period of individual waves. The meaning of these very general remarks can best be illustrated with specific examples.

Application to tsunamis

Theory--For low waves in water of depth h the velocity is given by the equations

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi h}{L} \qquad (25a)$$

or

$$C = \frac{gT}{2\pi} \tanh \frac{2\pi h}{CT} \qquad (25b)$$

Equations (25) were originally derived for an infinitely long wave train of constant period, but it has been shown by Cauchy and Poisson [LAMB, 1932] that they apply also to a wave system of gradually varying period. It has been customary to state that in very shallow water, that is, water where

$$h < 0.05L \qquad (26)$$

(25) reduces to the well-known form

$$C^2 = gh \equiv C_o^2 \qquad (27)$$

according to which the velocity depends upon depth only, and the propagation is therefore nondispersive.

Condition (26) is certainly fulfilled by all known tsunamis, and accordingly (27) has been applied for computing travel times. These attempts have been remarkably successful.

There are, however, certain secondary phenomena associated with the propagation over long distances, such as a very gradual increase in wave period, for which (27) is no longer a satisfactory approximation. The first two terms in the expansion of a hyperbolic tangent are

$$\tanh\alpha = \alpha - (\alpha^2)/3 \qquad (28)$$

and to the same degree of approximation (27) becomes

$$C^2 = C_o^2[1 - (\alpha^2)/3] \qquad (29)$$

where

$$\alpha = 2\pi h/L = 2\pi h/CT \qquad (30)$$

For small values of α^2

$$\sqrt{1 - (\alpha^2)/3} = 1 - (\alpha^2)/6 \qquad 1/[1 - (\alpha^2)/6] = 1 + (\alpha^2)/6 \qquad (31)$$

and

$$(C_o - C)/C_o = (\alpha^2)/6 \qquad (32)$$

Percentage differences in the velocity of very long waves are therefore of the order of α^2. The rotation of the Earth also introduces dispersion, and for tsunamis of half-hour period or longer this effect cannot be neglected. But in the case of the short-period tsunami of April 1, 1946, the Earth's rotation increases the total dispersion by less than one per cent.

Differentiating (25b) gives

$$\partial C/\partial T = (g/2\pi)\left\{(\tanh\alpha - \alpha\,\mathrm{sech}^2\alpha)/[1 + (C_o{}^2/C^2)\,\mathrm{sech}^2\alpha]\right\} \quad \ldots\ldots\ldots\ldots (33)$$

which can, in view of (29) and the expansion

$$\mathrm{sech}\,\alpha = 1 - (\alpha^2)/2, \quad \mathrm{sech}^2\alpha = 1 - \alpha^2 \quad \ldots\ldots\ldots\ldots (34)$$

be reduced to the following form:

$$\partial C/\partial T = g(\alpha^3)/6\pi \quad \ldots\ldots\ldots\ldots (35)$$

Substituting into (14) gives

$$V = C_o[1 - (\alpha^2)/2] \quad \ldots\ldots\ldots\ldots (36)$$

or, in terms of percentage differences

$$(C - V)/C_o = (\alpha^2)/3 \quad \ldots\ldots\ldots\ldots (37)$$

A comparison with (32) leads to the interesting result

$$C - V = 2(C_o - C) \quad \ldots\ldots\ldots\ldots (38)$$

so that for any given wave period the group velocity is smaller than the wave velocity by twice the amount that the wave velocity is smaller than the velocity of infinitely long waves.

Substituting (36) into (20) and (21) gives the following relationships for the changes in period of individual waves.

$$\frac{dT}{dT} = -\frac{\alpha^2}{3}\frac{\partial T}{\partial T} = \frac{\alpha^2}{3}C_o\frac{\partial T}{\partial x} \quad \ldots\ldots\ldots\ldots (39\text{ a, b})$$

$$\frac{dT}{dx} = -\frac{\alpha^2}{3}\frac{1}{C_o}\frac{\partial T}{\partial t} = \frac{\alpha^2}{3}\frac{\partial T}{\partial x} \quad \ldots\ldots\ldots\ldots (40\text{ a, b})$$

The general integral (17) can now be written in the form

$$T = T(t - t_o - I/T^2) \quad \ldots\ldots\ldots\ldots (41)$$

where

$$t_o = (1/\sqrt{g})\int h^{-1/2}dx \qquad I = (2\pi^2/g^{3/2})\int h^{1/2}dx \quad \ldots\ldots\ldots\ldots (42)$$

If the bottom profile along the path of travel is approximated by n short straight line segments, from x_o, h_o to x_1, h_1; from x_1, h_1 to x_2, h_2; . . . , from x_{n-1}, h_{n-1} to x_n, h_n, then in the interval (i - 1) to i

$$h = h_{i-1} + \frac{h_i - h_{i-1}}{x_i - x_{i-1}}(x - x_{i-1}) \quad \ldots\ldots\ldots\ldots (43)$$

and (42) can be integrated along each line segment:

$$t_o = \frac{2}{\sqrt{g}}\sum_{i=1}^{n}\frac{1}{\sqrt{h_i} + \sqrt{h_{i-1}}}(x_i - x_{i-1}), \qquad I = \frac{4\pi^2}{3g^{3/2}}\sum_{i=1}^{n}\frac{h_i + \sqrt{h_i h_{i-1}} + h_{i-1}}{\sqrt{h_i} + \sqrt{h_{i-1}}}(x_i - x_{i-1}). \quad (44)$$

By tabulating corresponding values of h_i, x_i the integrals can be evaluated fairly rapidly.

The travel time t_o of an infinitely long wave can be computed according to

$$t_o = \int (1/C_o)dx \quad \ldots\ldots\ldots\ldots (45)$$

By setting $\Delta t = t - t_o$, (41) can be written in the more convenient form

$$T = T(\Delta t - I/T^2) \quad \ldots\ldots\ldots\ldots (46)$$

If the first arrival of the tsunami is clearly indicated on the record, and if the initial wave period exceeds ten minutes, Δt may, with sufficient approximation, be taken as the time interval after the first recorded arrival of the tsunami at a given station.

One particular form of the solution (46), and one that satisfies dimensional considerations, is

$$T = (1/a)(\Delta t - I/T^2) \quad \ldots\ldots\ldots\ldots (47)$$

where a is an arbitrary constant. Equation (47) represents a cubic equation in T,

$$T^3 - [(\Delta t)T^2/a] + I/a = 0 \quad \text{(48)}$$

with one or three distinct real roots, depending upon whether the discriminant

$$D = (4I/a)(\Delta t/a)^3 - 27(I/a)^2 \quad \text{(49)}$$

is positive or negative.

The simplest possible solution is found by setting $a = 0$ in (47):

$$T = \sqrt{I/\Delta t} \quad \text{(50)}$$

It is worth noting that even this simple solution exhibits some of the desired physical characteristics. For the earliest arrival of the waves Δt approaches zero, and T approaches infinity. For negative values of Δt, that is, for times preceding the arrival of the first wave, the solution for T is properly imaginary.

Whether (47) or (50) are valid can be decided by plotting the relationship (46) from observational data. If the relationship is linear, (47) may be used, and if the line furthermore coincides with the T axis, (50) may be used.

Observations--Figure 2A shows the general refraction pattern of the tsunamis formed by the submarine earthquake of April 1, 1946. The dashed curves give the positions of the crests at stated time intervals, and the solid lines, which are normal to the crests, give the paths of travel towards various stations. There are two alternate routes into Honolulu and La Jolla. The graph, which was prepared by the Department of Engineering, University of California [ANONYMOUS, 1946], probably represents the first attempt to apply the principles of refraction diagrams [UNITED STATES HYDROGRAPHIC OFFICE, 1945] to a study of tsunamis. Figure 2A also gives the approximate paths of two other tsunamis recorded at Honolulu about 25 years ago.

Figure 2B shows the depth profiles along various paths of travels; from these, t_0 and I have been evaluated according to (43) and (44), and summarized in Table 1 together with other pertinent data.

Table 1--Data for tsunamis

Date	Time	Epicenter	Station	x	t_0	I
	h m			naut mi	h m	min^3
April 1, 1946	12 28.9	Unimac Island, 54°N, 164°W	Honolulu, east	1976	04 34	725
			Honolulu, west	2025	04 34	789
			Honolulu, mean	2000		757
			San Luis Obispo	2168	05 36	789
			La Jolla, east	2410	06 11	849
			La Jolla, west	2441	06 11	868
			La Jolla, mean	2425		859
			Matarani	6389	16 26	2220
			Valparaiso	7050	18 07	2471
April 13, 1923	05 17, Honolulu time	Kamchatka, 56°N, 162°E	Honolulu	2756	07 23	1101
November 10, 1922	00 03, Honolulu time	Chile	Honolulu	5992	14 57	2079

C. K. Green, United States Coast and Geodetic Survey, has kindly put at our disposal the tidal records which formed the basis of his recent discussion [GREEN, 1946]. The five best records have been selected, and the changes of period with time at the five corresponding stations have been found in the following manner.

Consecutive crests and troughs were numbered (see Fig. 3A) and plotted against Δt, the time interval after the initial arrival of the tsunami (see Fig. 3B). The period was then determined from the slope of the curves in Figure 3B, and plotted in 3C. In addition to this method, groups of particularly well-defined crests and troughs were selected from the tidal record, the period measured directly, and then plotted in Figure 3C.

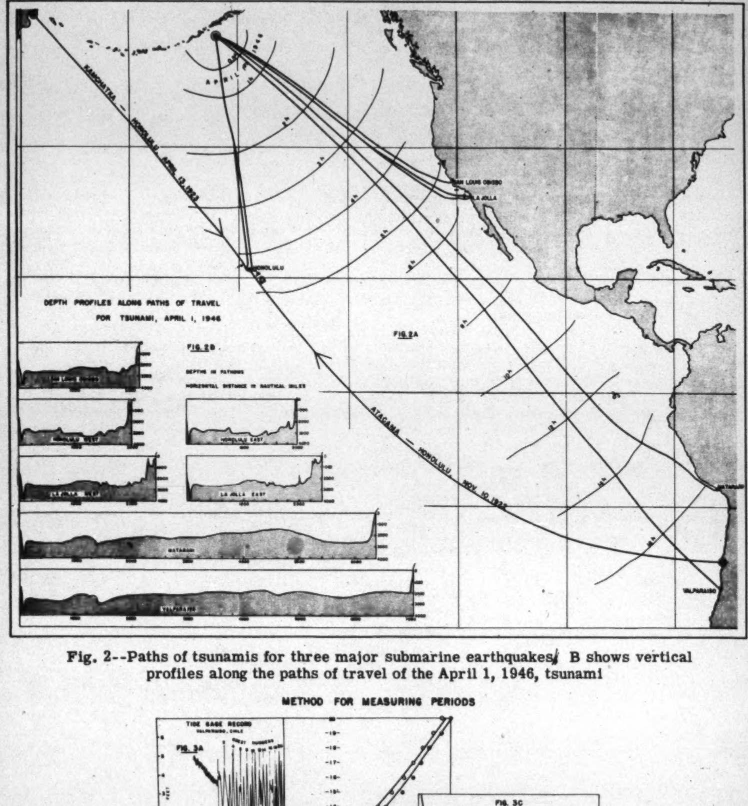
KAMCHATKA — HONOLULU APRIL 13, 1923
ATACAMA — HONOLULU NOV 10 1922
APRIL 1, 1946
HONOLULU
SAN LUIS OBISPO
LA JOLLA
MATARANI
VALPARAISO
FIG.2A
DEPTH PROFILES ALONG PATHS OF TRAVEL FOR TSUNAMI, APRIL 1, 1946
FIG.2B
DEPTHS IN FATHOMS
HORIZONTAL DISTANCE IN NAUTICAL MILES
SAN LUIS OBISPO
HONOLULU WEST
HONOLULU EAST
LA JOLLA WEST
LA JOLLA EAST
MATARANI
VALPARAISO

Fig. 2--Paths of tsunamis for three major submarine earthquakes; B shows vertical profiles along the paths of travel of the April 1, 1946, tsunami

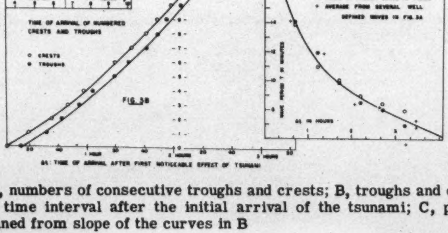

Fig. 3--A, numbers of consecutive troughs and crests; B, troughs and crests plotted against time interval after the initial arrival of the tsunami; C, plot of period determined from slope of the curves in B

Figure 4A gives the relationship of period with time at the five selected stations. The relatively short periods of the tsunami of April 1, 1943, interference between waves traveling over different paths, and the superposition of seiches greatly reduce the accuracy with which periods can be measured. Certain portions of the records at San Luis Obispo and La Jolla had to be omitted because of severe seiche formation. At Honolulu a three-minute seiche is predominant after the first hour, and the measured periods from the nearby Waima River water-stage recorder have been taken into account in drawing the curve. It would be desirable to apply more refined methods of period analysis, but these are made difficult by the slow recording speed (one hour = one inch) and the resulting extreme vertical exaggeration of the record.

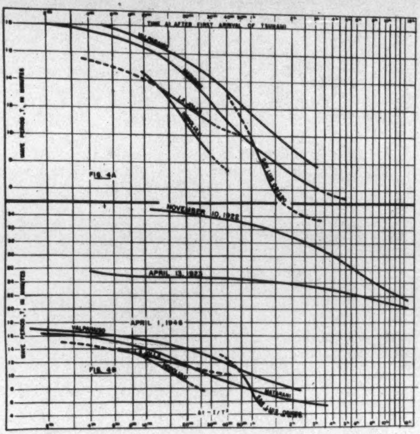

Fig. 4--A, period against time of April 1, 1946, tsunami at various stations; B, plot of general solution (17) for three different earthquakes

Comparison between theory and observations--The observed field of wave period is in qualitative agreement with the theoretical considerations. The period increases with distance of travel, but decreases with time at every given station.

For a quantitative check, corresponding values of T, Δt (see Fig. 4A), and I (see Table 1) were substituted in the general field solution (46) and plotted in Figure 4B.

In accordance with the theory all observations pertaining to the tsunami of April 1, 1946, from Hawaii to Chile, obey the same general relationship, while observations of the two other tsunamis follow a different relationship. Thus the indeterminateness of the function in the general solution (46) depends upon the nature of the original disturbance. Preliminary considerations indicate that long periods in Figure 4B indicate a large horizontal extent of the initial disturbance. Perhaps the size and shape of the initial disturbance could be estimated by assuming certain forms of the initial deformation, or initial impulse, for which an analysis of the Cauchy-Poisson type can be carried through, and then constructing a network of lines on Figure 4B corresponding to various types and sizes of the initial boundary conditions. A comparison of this network with observed relationships, such as the ones in Figure 4B, may yield information regarding the nature and size of the original disturbances.

A feature which is obscured by the logarithmic scale of the abscissa is that the leading wave, especially the portion of the wave preceding the first crest, is associated with small values of $\Delta t - I/T^2$, and large values of T. Therefore a in (47) must be small and the approximate solution (50) is applicable, so that the periods of the very first waves, the "forerunners" are approximately proportional to $\sqrt{I}$ and inversely proportional to $\sqrt{t}$.

From any one complete record it is possible to compute the periods at any of the other stations. Assuming the Matarani record to define the relationship for the tsunami of April 1, 1946, the periods for all other stations have been computed for various values of Δt, and plotted against the observed periods (see Fig. 5). The observed wave periods in the North Pacific tend to be somewhat shorter, those at Valparaiso longer than the computed periods. The same conclusion follows directly from (40a), which gives an average increase in the period of the first wave of 1.3 minutes in 5000 miles. GREEN [1946] has measured the time interval between the first crest and first trough and on that basis estimates the period increase of the first wave to amount to 2.0 minutes in 5000 miles. The observational data are too inaccurate to determine whether this discrepancy is significant, and whether it therefore indicates a more rapid increase in period than the increase due to dispersion. (" . . . the amount of increase in period is difficult to determine from the present records. For instance the table shown in my paper indicates an increase of around two minutes. But by dropping the shortest period station from the California group, and the longest period station from the Peru-Chile group, the mean value of increase in period would be 1-1/3 minutes from California to South America." [C. K. Green, July 18, 1946, personal communication to the author])

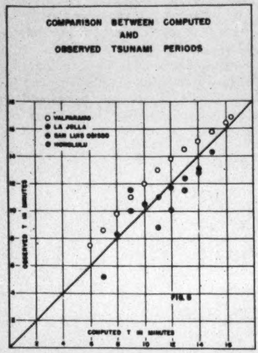

Fig. 5--Computed wave periods based upon (17) and the observed periods at Matarani, Peru

Application to swell

Theory--For low waves in deep water, the velocity depends upon wave length alone, or period alone,

$$C = \sqrt{gL/2\pi} = gT/2\pi \quad \ldots\ldots (51)$$

and the following formulae are therefore much simpler than in the case of tsunamis. Equations (8) and (14) lead at once to the well-known relationships

$$V_T = V_L = V = C/2 \quad \ldots\ldots (52)$$

Equations (20) and (21) give

$$\frac{dT}{dt} = -\frac{\partial T}{\partial t} = \frac{C}{2}\frac{\partial T}{\partial x} \qquad \frac{dT}{dx} = -\frac{1}{C}\frac{\partial T}{\partial t} = \frac{1}{2}\frac{\partial T}{\partial x} \quad \ldots\ldots (53)$$

Equation (17) reduces to

$$T = T(t - \sigma x/T) \ldots\ldots (54)$$

where $\sigma = 4\pi/g$ (dimensions t^2/L). The integral (54) has been given by ROSSBY [1945].

The special case corresponding to (47) gives

$$T = (t/2a)(I \pm u) \quad \ldots\ldots (55)$$

where $u = \sqrt{1 - 4\pi ax/t^2}$; if, furthermore, a = 0 (50)

$$T = \sigma x/t \quad \ldots\ldots (56)$$

which is a solution of the Cauchy-Poisson wave problem [LAMB, 1932].

It will be shown that the special solution (56) is in good agreement with observations of the "forerunners" of swell from a distant storm. This is assumed to justify the use of the simple solution for all further derivations, though the agreement might also have been expected from the analogy with the forerunners of the tsunami. The following discussion deals therefore exclusively with the forerunners, and is not applicable to the visible swell. Some of the following derivations could have been given for the general case, but the not inconsiderable difficulties involved in dealing with a moving source are greatly simplified by working with the special solution.

To derive the equations for individual waves, T can be eliminated between (51) and (56), $dx/dt \equiv C = gT/2\pi = 2x/t$. Integrating gives

$$x/x_D = (t/t_D)^2 \quad \ldots\ldots (57)$$

$$T/T_D = t/t_D = \sqrt{x/x_D} \qquad (58)$$

$$\partial T/\partial t = -\sigma x/t^2 = -T/t \qquad (59)$$

The subscript "D" may refer to any fixed point on the wave's journey, but will here be taken to denote conditions at the wave station. If T_D and $(\partial T/\partial t)_D$ are determined from the wave record, then the distance and time of travel can be computed from (59):

$$x_D = T_D^2/\sigma(-\partial T/\partial t)_D \qquad t_D = T_D/-(\partial T/\partial t)_D \qquad (60\text{ a, b})$$

Waves from a moving storm--Application of these equations to the study of swell is difficult, because one must deal with a moving source of finite size which continuously emits new waves. It will be assumed that the problem can be treated as one involving an infinite number of instantaneous sources, each independently emitting a wave field according to the assumptions made earlier. Let x and t retain their former meanings, designating the total distance and time, respectively, that any wave has traveled. The fixed coordinated system will be denoted by χ and τ, χ representing distance from the wave origin to the wave station, and τ the time on some standard scale, for example, GCT.

The movement of the storm center is represented by the equation

$$\chi_c = \phi(\tau) \qquad (61)$$

Let $\delta\chi$ be the distance of a point of wave origin from the storm center, so that

$$\chi = \chi_c + \delta\chi \qquad (62)$$

Waves arriving at the wave station at any time τ were generated at a time $\tau - t$ when the storm center was located at

$$\chi_c = \phi(\tau - t) \qquad (63)$$

To determine the period at the wave station at a time τ, set $x = \chi = \phi(\tau - t) + \delta\chi$ and substitute into (56)

$$T = \sigma[\phi(\tau - t) + \delta\chi]/t \qquad (64)$$

At any time τ a spectrum of wave periods must be present at the wave station, because of two factors: (a) Waves arrive simultaneously from different sectors of the storm (different values of $\delta\chi$); and (b) waves arrive simultaneously, although they were generated at different times (different values of t).

The total width of the period "band" is given by

$$\Delta T_\tau = [\partial T/\partial(\delta\chi)]F + (\partial T/\partial t)Q \qquad (65)$$

where F is the effective length of the storm fetch at a time $(\tau - t)$, and Q is the time interval during which waves perceptible at the station were generated. Partial differentiation of (64) leads to the expressions

$$[\partial T/\partial(\delta\chi)]F = \sigma F/t, \quad (\partial T/\partial t)Q = -(\sigma/t)(V - U)Q \qquad (66\text{ a, b})$$

where

$$U = -[\partial\phi/\partial(\tau - t)] \qquad (67)$$

is rate of the storm movement towards the wave station at the time $(\tau - t)$, and $V = \chi/t$ the group velocity.

Equations (66) may also be interpreted to give the width in the period band due to the instantaneous actions of a finite storm (66a), and due to a moving point source (66b), respectively. The longest periods in the band are those of the earliest perceptible waves from the furthest sector of the storm; the shortest periods are due to the waves generated latest near the leading edge of the storm.

The shift in period of the band as a whole will be interpreted with the aid of an actual example. It will be shown that the shift is related to the position and speed of the storm, and can therefore provide clues regarding changes in the meteorological situation. The width and appearance of the band should provide some information about the size and character of the storm itself.

Observations--Unfortunately no simultaneous wave records from two or more well-separated stations are available to test the theory. The proposed wave recording stations at La Jolla, California, and San Nicolas Island, 120 miles west-northwest from La Jolla can be expected to give valuable information. Observation shows that the increase in swell period for an individual wave may be of the order of two seconds a day [SVERDRUP and MUNK, in press]. According to (53), for an average period of ten seconds, $\partial T/\partial t = -2$ sec/day $= -2.3 \times 10^{-5}$ sec/sec; $\partial T/\partial x = 0.94 \times 10^{-6}$ sec/ft $= 6 \times 10^{-3}$ sec/naut mi. The corresponding period difference over 120 miles is about 0.7 second. Both $\partial T/\partial t$ and $\partial T/\partial x$ can therefore be measured with existing instruments. Comparison of the observation with the foregoing considerations would show whether the assumptions made in this report are applicable to swell, and especially whether the significant waves, that is, the highest waves present, and the ones that determine the character of the surf, maintain their identity.

Some confirmation of the applicability of the theory to a long swell can be found in records from a single wave station at Pendeen, England. (The Oceanographic Research Group, Admiralty Research Laboratory, Teddington, England, have kindly placed at our disposal unpublished records of swell at Pendeen, near Lands End.) The waves were measured by means of a differential pressure recorder on the ocean bottom at an average depth of 114 feet. The records were then analyzed for period by a frequency analyzer, specially designed for that purpose at the Admiralty Research Laboratory.

Figure 6 shows a set of period analyses of 20-minute records taken at intervals of two hours. The abscissa give simply wave periods in seconds, but the ordinates are more difficult to interpret, depending both upon the frequency of occurrence of a certain period, and upon the corresponding wave height.

The band of gradually diminishing periods in Figure 6 is the result of an intense cyclone which formed off the coast of Cuba, 3000 miles from Pendeen, on March 10, 1945, and traveled in a general northeasterly direction, passing west of the British Isles. The positions of the forward and rear edges of the storm are given in Figure 7A. These were determined from six-hourly weather maps, following the rules for measuring fetches for wave forecasting [UNITED STATES HYDROGRAPHIC OFFICE, 1944]. Four representative weather maps are included in Figure 7. The weather maps were drawn and analyzed at the United States Navy Weather Central, Washington, D. C.

The first indications of the storm on the wave record are some "low-frequency noises" at $14^{h}00^{m}$ GCT, March 14, 1946. At that time visual observations at Pendeen noted only the presence of ten- to 12-second waves from local winds. The long "forerunners" of the swell were too low to be visible. The upper and lower limits of the period band have been read off the record and drawn on Figure 7B to emphasize the similarity between the recorded wave periods and the observed storm paths. A relationship between the width of the period band and the fetch is also apparent. The implications of (64) - (66) are therefore borne out by the observations. It will be shown, however, that the similarity of the curves in Figure 7 may be misleading, and that great care must be exercised in the interpretation of the wave records.

Comparison between theory and observations--We shall first deal with the lower boundary of the period band. The initial waves from the storm of March 10 to 13, 1946, reached Pendeen around $16^{h}00^{m}$, March 14, 1946, with a minimum period of 19 seconds. Let this time and period be designated by τ_0 and T_{τ_0}, and let χ_0 and $\tau_0 - t_0$ refer to the distance from Pendeen and the time of wave origin. Then the period recorded at time τ_0 equals:

$$T_{\tau_0} = \sigma\chi_0/t_0 \quad \ldots\ldots\ldots\ldots \quad (68)$$

Assume that the "instantaneous" disturbance which gave rise to the waves described in (68) was the only existing source of the waves present; then slower waves with shorter periods would follow the faster longer waves, so that the period at the wave station would decrease with time according to the equation

$$T_{\tau} = \sigma\chi_0/t \quad \ldots\ldots\ldots\ldots \quad (69)$$

where $(\tau - t) = (\tau_0 - t_0)$ is the time of the disturbance. Therefore, as long as the lower limit of the band is defined by the waves from a single instantaneous disturbance,

$$\partial T/\partial\tau = \partial T/\partial t \quad \ldots\ldots\ldots\ldots \quad (70)$$

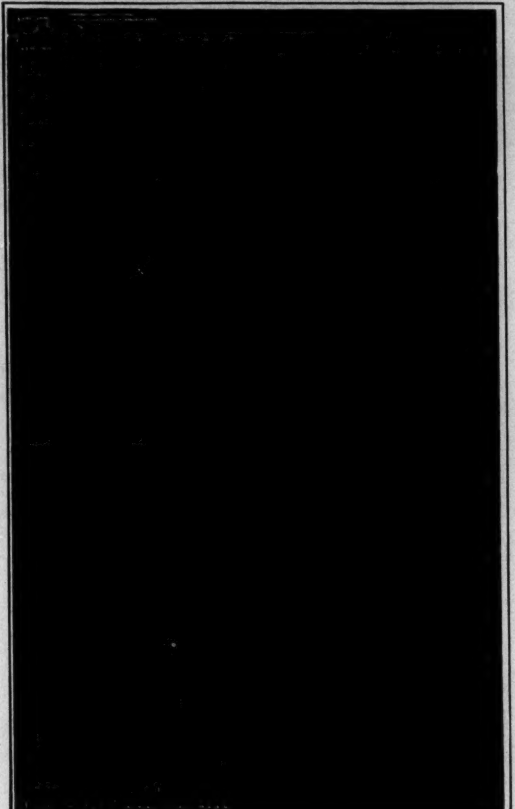

Fig. 6--Spectogram of waves at Pendeen, England, at two-hour intervals from March 14, 1946, 04^h00^m to March 16, 1946, 12^h00^m

Let another instantaneous disturbance at a time $\tau - t + \Delta\tau$ and distance $\chi' = \chi - \Delta\chi$ generate a system of waves which arrives at Pendeen simultaneously with the first system, thus having traveled a time interval $t' = t - \Delta\tau$. The period of waves from the second disturbance at time τ equals $T_\tau' = \sigma(\chi - \Delta\chi)/(t - \Delta\tau)$, and

$$T_\tau' - T_\tau = \frac{\sigma}{(t - \Delta\tau)}\left(\frac{\chi}{t} - \frac{\Delta\chi}{\Delta t}\right)\Delta\tau \quad \ldots\ldots\ldots\ldots\ldots\ldots (71)$$

As the time and distance between the two disturbances is decreased without limits, (71) approaches the differential equation (66b) for a moving point source. According to (51), (52), and (56)

$$\chi/t = V = T/\sigma \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (72)$$

and

$$\Delta\chi/\Delta t = \overline{U} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (73)$$

can be considered the average velocity of the storm movement between any two points. Therefore, T′ is higher than, equal to, or lower than T according to whether V is larger than, equal to, or smaller than $\overline{U}$. For T = 19 seconds, V = 29 knots, while $\overline{U}$ during the first day of storm was about 17 knots. Since the forerunners of the swell travel at considerable speed, the initial decrease of the lower limit of the band results from the characteristics of a single wave system from the earliest perceptible disturbance, and is therefore similar to the decrease of the tsunami period at a fixed station. The time and position of the origin of this wave system can be plotted as a point in Figure 8A, where it should fall within the observed storm track. The point will be called the "focus" of a certain portion of the wave-band boundary. The circles in Figure 8 give the lower limits of the period band, as they were measured on the Pendeen record. The position of the focus is computed in the following manner: (1) At the time τ = March 14, 1946, $18^{h}00^{m}$, Figure 8 shows T = 18.2 seconds, $\partial T/\partial\tau = -0.18$ sec/hr; (2) Equations (70) and (60) give χ = 2800 naut mi, t = 102 hr; (3) March 14, 1946, $18^{h}00^{m}$ minus 102 hours is March 10, 1946, $12^{h}00^{m}$. The position of the focus is shown by the large circle marked A in Figure 7A, and falls well within the observed storm track; (4) Setting χ_0 = 2800, and τ = March 10, 1946, $12^{h}00^{m}$ + t in (69) plot T_τ for various values of t in Figure 8.

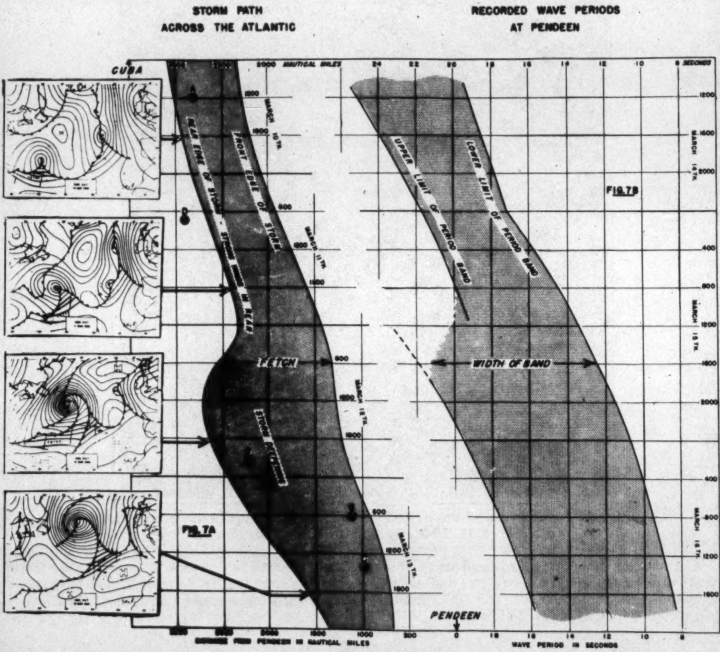

Fig. 7--Storm path across Atlantic, showing similarity in appearance to recorded wave periods at Pendeen. Points A--E in Figure 7A are locations of wave origin computed from wave records, suggesting possibility of using wave observations for tracking storms

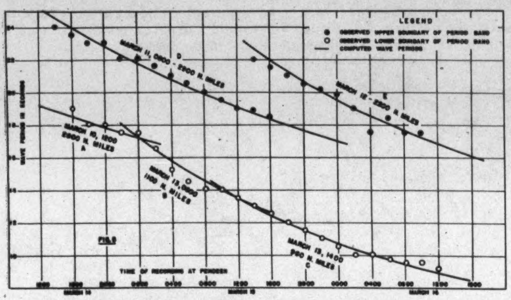

Fig. 8--Method for locating points A--E in Figure 7

On March 15, 1946, at 00^h00^m, the lower band changes its slope abruptly. The wave system from the original disturbance no longer constitutes the lower boundary of the period band. The new focus can be located by the same methods as before, and one obtains $X = 1100$ naut mi, on March 13, 1946, at 06^h00^m. It is remarkable that the storm during the interval from March 10, 1946, 12^h00^m to March 13, 1946, 06^h00^m does not contribute anything to the lower boundary of the period band. The final portion of the record can be fitted by a single curve from focus C at $X = 960$ naut mi, March 13, 1946, 14^h00^m.

The distance between the first two foci is 1700 naut mi, the time interval 66 hours, and $\overline{U}$ equals, therefore, 25.8 knots or 43 feet per second. According to (72) and (73) the two associated curves in Figure 8 should intersect at $T = \sigma \overline{U} = 16.8$ seconds. Actually the intersection takes place at $T = 17.2$ seconds.

The foregoing considerations lead to the following rules for the interpretation of the lower boundary of the period band: (1) During any time interval of continuously decreasing slope the boundary is determined by the wave system from a single focus. The focus can be located by measuring T and $\partial T/\partial t$ at any point within the interval, and applying (60) and (70); (2) A discontinuous increase in slope indicates an abrupt change from one focus to another. The intersection $T = \sigma \overline{U}$ gives the mean velocity $\overline{U}$ between the two foci; (3) A gradual increase in slope can be formed only by an envelope to a family of curves from adjoining foci. This situation can arise only in the case of a decelerating storm movement, according to the equation $U = T/\sigma$, where T is the recorded period along the envelope.

These rules constitute a possible means of tracking storms. It will be noticed, however, that focus A in Figure 7A is located 500 miles behind the storm front, the other two foci about 200 miles behind the front. This discrepancy must be expected, since waves generated at the front itself could not gather sufficient energy to be perceptible at the wave station; furthermore, the distance between the point of wave origin and the storm front must be larger for the first disturbance, which is almost 3000 miles from Pendeen.

The upper boundary of the period band depends upon the distribution of energy among waves of various periods and upon the sensitivity of the recording instrument. If a storm emits a complete spectrum of waves, as may indeed be the case, then waves whose periods are five minutes or longer would travel as shallow water waves similar to tsunamis from an earthquake, and would constitute the upper limit of the period band. But even if those very long period waves should be of height similar to the recorded waves they would not record because of the unfavorable response characteristics of the instrument.

Since the upper limit of the period band is well defined, we have applied the same methods as to the lower boundary. Between 14^h00^m and 18^h00^m on March 15, 1946, two upper boundaries can be recognized on the record, both of which are marked. The time and position of foci D and E have been computed and plotted on Figure 7A. Focus D lies somewhat behind the far boundary of the storm track, focus E somewhat short of it.

Figure 9 illustrates the application of the method to a more complicated meteorological situation, where it appears possible to recognize and place two simultaneous storms from the wave record. The good agreement between theory and observations bears out the validity of the special solution (56), and of the relation (58) according to which the period of an individual forerunner is proportional to the travel time and to the square root of the travel distance.

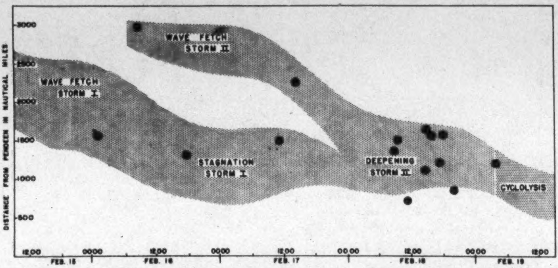

Fig. 9--Paths of two storms across the Atlantic (Points give position of wave origin computed from wave records at Pendeen)

Although it is too early for any definite predictions, the theory for the increase in wave period seems to provide a rational basis for the interpretation of wave records as an aid to weather forecasting. The forerunners of the swell are especially suitable for a "seaborne storm warning" because they arrive much sooner than the ordinary swell, because they give a simple record since their group velocity exceeds the velocity of storm travel, and because the special solution (56) is most likely to be applicable. For these reasons it would be advisable to work with periods even higher than those recorded at Pendeen. If the recording unit should be placed in deeper water where it is out of reach of the ordinary swell, then it could be designed to record the low forerunners with great sensitivity. The proposed wave-recording station at the Scripps Institution is designed to meet some of these requirements.

Application to seismic waves

Theory--The velocity of seismic surface waves, that is, of Love and Rayleigh waves, depends greatly upon the structural unit over which the waves are transmitted. Thus the average velocity of Love waves through the basin of the Pacific Ocean is roughly 15 per cent higher than across continental America.

Within each structural unit the velocity depends also on the wave period for the following reason: The transmitting medium consists usually of horizontal layers with different elastic constants. Short waves are transmitted through a thin upper layer and travel with its characteristic velocity; long waves spread their energy into lower layers and travel at a velocity approximately equal to a weighted mean velocity of the disturbed layers.

Unfortunately it is not possible, as it was for the tsunami and swell, to write a simple analytical expression for the relationship between period and velocity. Even for the simplest case of two uniform layers the expression is complicated, and for assumptions conforming more closely to actual conditions the theory becomes too cumbersome to be useful here [MEISSNER, 1927].

It is easier to work directly with empirical relationships such as those compiled by GUTENBERG and RICHTER [1936] from a large number of observations. These empirical relationships are between group velocity and period, but a knowledge of the wave velocity is also required for the application of our theory. If the elastic constants are functions of depth only, and do not vary along the path, then the group velocity is defined by

$$V = C/[1 + (T/C)(dC/dT)] \quad \text{.....................} \quad (14)$$

Multiplying numerator and denominator by CdT, and setting

$$L = CT \quad \text{.........................} \quad (10)$$

one obtains $dL/L^2 = dT/VT^2$. Integrating between the limits T and ∞ gives $1/L = \int_T^\infty (dT/VT^2)$, and finally, going back to (10):

$$1/C = T \int_T^{\infty} (1/VT^2)dT \qquad (74)$$

The rate of period increase of an individual wave

$$\frac{dT}{dx} = \left(\frac{1}{V} - \frac{1}{C}\right)\left(- \frac{\partial T}{\partial t}\right) \qquad (21a)$$

can now be computed from (74), the empirical relationship V = V(T), and the measured decrease of period with time at a given station.

General observations--MACELWANE [1923], who also made the problem of period increase the subject of his doctor's dissertation, obtained an average value of $dT/dx = 1.4 \times 10^{-8}$ sec/cm for the California earthquake of January 31, 1922. This figure represents the increase in period of waves occurring two and four minutes after the first arrival of surface waves, and this increase must be somewhat larger than the corresponding increase of individual waves. GUTENBERG [1939] suggests an equation of the form

$$T^2 = T_o^2 + ax/V^3 \qquad (75)$$

for the period increase of an individual wave, and gives a value of $a \approx 10^{10}$ cm²/sec for seismic surface waves. For various values of T, and corresponding values of V [GUTENBERG and RICHTER, Fig. 1, 1936] (75) gives the values shown in Table 2. The cauda of the surface waves increases in period at the rate of $dT/dx = 1.4 \times 10^{-8}$ sec/cm [GUTENBERG and RICHTER, Fig. 5, 1936]. BYERLY [1926] has made a careful study of the Montana earthquake of June 28, 1925, and his data indicates dT/dx to lie between 1.4×10^{-8} and 1.8×10^{-8} sec/cm.

Table 2--Values of T and corresponding values of V

T	V	dT/dx
sec	km/sec	sec/cm
10	3.45	1.2×10^{-8}
15	3.45	0.8×10^{-8}
20	3.5	0.6×10^{-8}
25	3.6	0.4×10^{-8}

All these estimates deal with long distance propagation from major shocks, and they consistently lead to an increase of the order of one second per 1000 km. To compare this value with theory the clearest records from American stations (Pasadena, Lick, Berkeley, and St. Louis) have been selected from Byerly's report on the Montana earthquake [BYERLY, 1926], and the average relationship between period and time plotted in Figure 10D. The relationship V = V(T) is again taken from Figure 1, GUTENBERG and RICHTER [1936], and the wave velocity shown in Table 3 is found by numerical integration of (74). The computed and observed period increases are therefore of the same order of magnitude.

Table 3--Numerical integration of (74)

T	V	C (74)	∂T/∂t (Fig. 10D)	dT/dx
sec	km/sec	km/sec	sec/sec	sec/cm
10	3.56	3.76	0.058	0.9×10^{-8}
12	3.52	3.80	0.110	2.3×10^{-8}
14	3.50	3.85	0.18	4.8×10^{-8}

The Mexican earthquake, February 22, 1943--Figure 10A shows records of this shock at the various stations maintained by the Pasadena Seismological Laboratory. C. F. Richter of the Seismological Laboratory, Pasadena, has gone to considerable trouble in selecting a set of records suitable for this discussion. Tracing individual waves from station to station by making use of the known distances and wave velocities has been attempted, but the identification, which is difficult, especially for the furthest station, is not essential to the following analysis.

Figure 10B shows the relationship between period and time at the four stations. Figure 10C is a plot of the basic solution (17) provided that the transmission characteristics are uniform in the x direction, so that

$$T = T(t - x/V) \qquad (76)$$

where t is time (GCT), V is the group velocity, and x is the excess of the travel distance over the distance to La Jolla. The theory is confirmed by the fact that observations for the four stations obey a single relationship. The procedure is analogous to the one followed earlier in the analysis of the tsunami of April 1, 1946. The similarity between the curves in Figures 4B and 10C is striking and suggests the possibility that the nature of the general solution (76) may serve as a means of estimating the horizontal extent of the initial seismic disturbance.

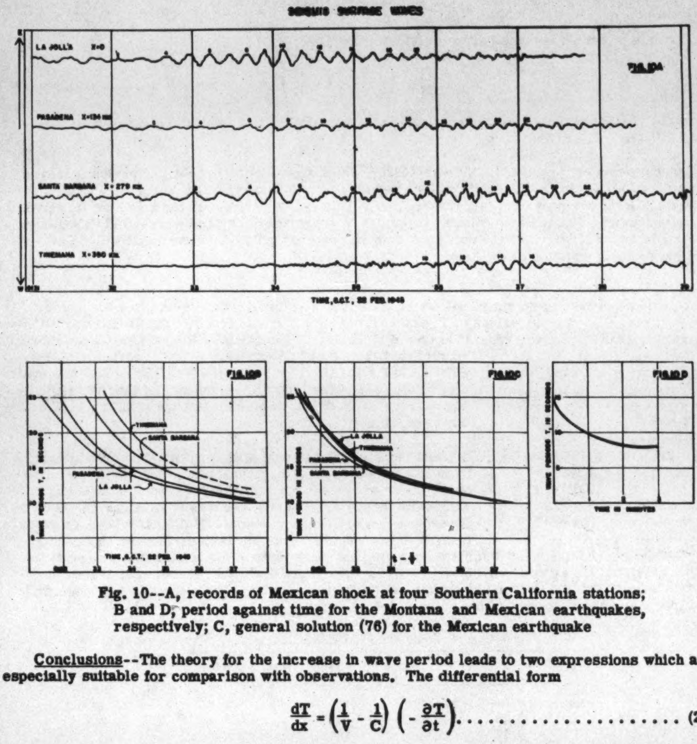

Fig. 10--A, records of Mexican shock at four Southern California stations; B and D, period against time for the Montana and Mexican earthquakes, respectively; C, general solution (76) for the Mexican earthquake

Conclusions--The theory for the increase in wave period leads to two expressions which are especially suitable for comparison with observations. The differential form

$$\frac{dT}{dx} = \left(\frac{1}{V} - \frac{1}{C}\right)\left(-\frac{\partial T}{\partial t}\right) \quad \text{(21a)}$$

gives the period increase with distance of an individual wave of group velocity V, wave velocity C, and rate of period decrease at a fixed point $\partial T/\partial t$. Between two stations separated by a finite distance average values have to be used. The integrated form for the wave field requires that from a single disturbance all waves at any time t and distance x must obey the same functional relationship

$$T = T[t - \int (1/V)dx] \quad \text{(17)}$$

Both forms have been applied successfully to the examples in this report. However, each application poses its own particular problem. For the tsunami the variation in depth along the path of travel must be taken into account. In the case of the forerunners of the swell, complexities associated with a moving continuous source must be considered. For the seismic surface waves the dispersion relationship must be taken from empirical evidence.

Yet in spite of the fact that we have dealt with different geophysical phenomena the increase in period seems to follow the same physical law. The nature of the functional relationship in (17) is strikingly similar for the tsunami and the seismic surface waves. In all instances the period increase is slow except for the leading waves, whose periods are approximately proportional to their travel time and to the square root of their travel distance. From the experience gained it seems likely that other phenomena dealing with long-distance wave propagation can be brought into the same theoretical framework.

Acknowledgments--The assistance of various agencies and persons has been acknowledged at appropriate places in the text. I am especially indebted to C. K. Green, United States Coast and Geodetic Survey, and B. Gutenberg and C. F. Richter of the Seismological Laboratory, California Institute of Technology. Robert S. Arthur, U. S. N. R. has offered a number of suggestions, and C. J. Burke, A. A. F., has carefully read the manuscript and checked the mathematical equations. T. Saur, Jr. has helped with the computations. Although this is the first paper on waves which I have not written jointly with H. U. Sverdrup, the influence of his thinking pervades this investigation.

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PETROLOGY AND STRUCTURE OF THE MOA CHROMITE DISTRICT, ORIENTE PROVINCE, CUBA

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Abstract--Chromite deposits in the Moa district, on the north coast of Oriente Province, Cuba, form one facies of the ultramafic complex in which they occur. Two planar structures, one a compositional layering due to variations in the relative proportions of olivine, pyroxene, plagioclase feldspar, and chromite, and the other a foliation caused by the orientation of pyroxene crystals in peridotite, are in general parallel, but diverge in a few places. Dips are fairly constant, being moderate to the northwest over most of the area, but sharp reversals occur immediately adjacent to irregularities in the chromite deposits. Two prominent joint sets are present: (1) Cross joints striking parallel to the strike of the foliation and dipping approximately at right angles to it; and (2) longitudinal joints striking parallel to the direction of dip of the foliation and nearly vertical. Gabbro dikes follow the first set, chrysotile veins the second. Within the ore bodies dikes are commonly coarser-grained, larger, and far more abundant than in peridotite; they enclose coarse, angular fragments of chromite.

Structural relations indicate that the chromite deposits are of early-magmatic, probably pre-intrusion origin. It is proposed that gravity differentiation of a basaltic magma resulted in the formation of a chromite-rich layer near the base of a peridotite substratum. Downwarping of the crust led to intrusion of a crystal mush of olivine crystals and interstitial liquid which carried fragments of the chromite layer up as essentially solid blocks. Stresses set up during intrusion and consolidation produced the foliation and cross joints. Injection of gabbroic rest magma formed the dikes. Stresses continued into the stage of serpentinization, producing the longitudinal joints and opening channels for serpentinizing solutions.

The relation of the Moa intrusive mass to the layered Stillwater and Bushveld complexes is discussed.

Introduction

Location and accessibility--The Moa district, located in eastern Oriente Province, Cuba (see Fig. 1), extends some 25 miles from Loma Miraflores, ten miles east of Sagua de Tánamo, to the Rio Jiguaní, 20 miles northwest of the town of Baracoa (see Fig. 2). The district is bounded on the north by the coast and on the south by the crest of the Cuchillas de Toar, the range dividing the north-flowing streams from those tributary to the Rio Toa; it varies in width from ten to 15 miles. The eastern and southern boundaries have been chosen arbitrarily, as the district is only the northwestern part of a rugged highland area which continues nearly to Punta Maisí, the easternmost tip of the island. This region is one of the least populated and most inaccessible areas of

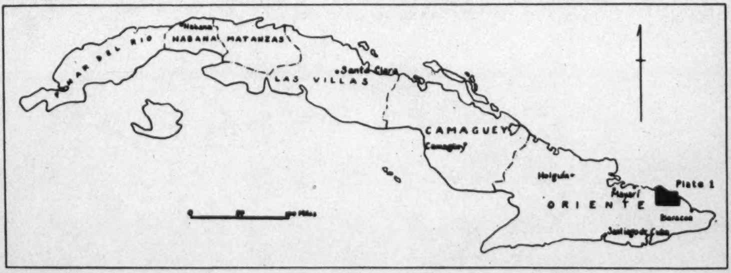
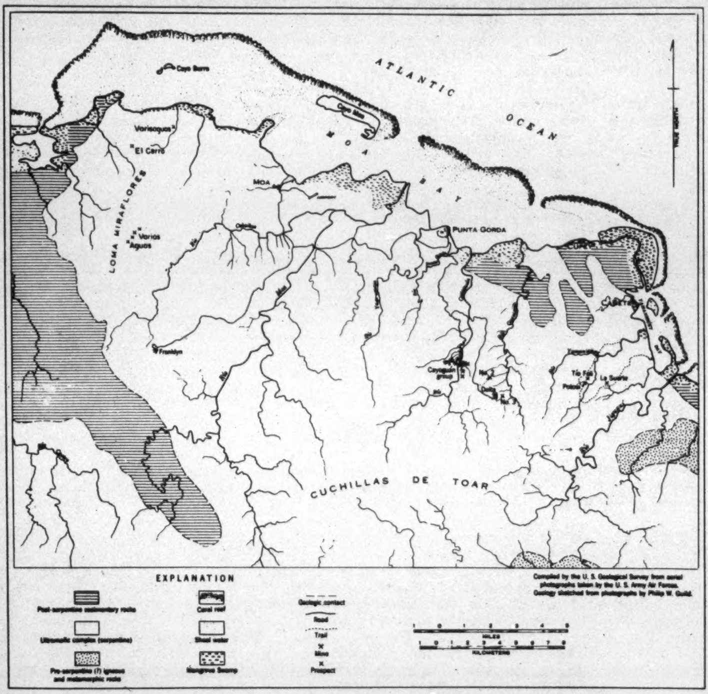


Fig. 1--Index map of Cuba showing location of the Moa district

Cuba, as it is not connected with the rest of the country by any roads or regular routes of overland travel. Formerly the only means of communication was by schooner or launch along the coast, but at present the daily plane from Santiago de Cuba to Baracoa will land at Moa upon request, providing a quick and easy means of transportation to and from the district. Within the district itself good roads connect all the developed mines to Moa and Punta Gorda, the shipping point on Moa Bay, and fair to poor roads used to haul timber to the sawmill at Moa give access to some of the remaining parts of the area, but the country is otherwise untraversed and almost impenetrable away from the coastal strip. The largest settlement within the district is Punta Gorda, headquarters for the chromite companies, which fluctuates in population with the state of mining activity; except for the sawmill at Moa there is no other commercial activity within the district, and the few inhabitants live in small villages and isolated houses along the shore.


ATLANTIC OCEAN
MOA BAY
Cayo Burro
Cayo Moa
El Cerro
MOA
LOMA MIRAFLORES
Varias Aguas
Franklyn
PUNTA GORDA
Potosí
La Suerte
CUCHILLAS DE TOAR
EXPLANATION
Post-serpentine sedimentary rocks
Ultramafic complex (serpentine)
Pre-serpentine (?) igneous and metamorphic rocks
Coral reef
Shoal water
Mangrove Swamp
Geologic contact
Road
Trail
Mine
Prospect
1 0 1 2 3 4 5
MILES
1 0 1 2 3 4 5 6 7 8
KILOMETERS

Compiled by the U. S. Geological Survey from aerial photographs taken by the U. S. Army Air Forces. Geology sketched from photographs by Philip W. Guild.

Fig. 2--Sketch map of the Moa chromite district, Oriente Province, Cuba

Geologic setting--The Moa district is a small part of the belt of serpentinized intrusive rocks extending not only the length of Cuba, but traced by HESS [see "References" at end of paper, [1938 a] from Guatemala on the west through Cuba to Hispaniola and Puerto Rico, thence south, by inference from the strip of negative anomalies, along the chain of the Lesser Antilles to the coast of South America, where other serpentine masses are found in a belt extending westward through Venezuela and the Dutch islands to the Cordillera Central of Columbia. Within Cuba the serpentine belt may be divided tectonically into two parts: (1) A highly-deformed zone in which extensive post-serpentine thrusting has occurred, and (2) a zone characterized by large, relatively undisturbed domical uplifts. The former includes the Camagüey and Holguín areas, the latter the Sierra de Nipe, Sierra del Cristal, and the Chuchillas de Toar, extending from the vicinity of Mayarí to Baracoa. The Moa district lies on the north flank of the last-mentioned range.

The oldest rocks of the region are chlorite schists, altered volcanic tuffs and lavas, and thin impure marbles, intruded by diorite, which compose the "basement complex" and are particularly well-exposed along the south coast of the island east of Guantánamo [MEINZER, 1933]. Although little is known about these rocks within the Moa district, THAYER [1942 a, pp. 9-10] has described a belt of dioritic igneous rocks south of Navas Bay, some eight miles to the east, and examination of aerial photographs indicates that the belt extends westward to the eastern edge of the district. The areas of non-serpentine rocks stand out sharply because of the finer grain of the stream pattern developed on them and the more luxuriant plant growth which their soils support. Another area just enters the district a few miles to the southwest. The serpentine shows no trace of the intense metamorphism which affected the rocks of the basement complex, nor have dioritic rocks been found in it. It is inferred, therefore, that the serpentine is intrusive into these rocks, although no direct evidence for this has been seen. As fossils are unknown from rocks older than Eocene in this region, no precise ages earlier than Tertiary can be assigned. Elsewhere in Cuba, however, serpentine cobbles have been found in Upper Cretaceous conglomerates. The basement rocks are tentatively dated as early Mesozoic or older. They have been involved in at least one more period of deformation than the serpentine.

Erosion of the metamorphic cover and an unknown thickness of the serpentine complex itself was followed by submergence and the deposition of limy sediments in early Tertiary time. These sediments, which once probably covered the entire district, were for the most part removed after domical uplift in the middle Tertiary. They occur today as scattered remnants overlying serpentine along the northeast coast, and in a deep embayment of the Sagua de Tánamo basin which lies to the west.

A prolonged period of weathering under tropical conditions, probably while the relief was moderate or slight, produced the deep mantle of ferruginous laterite which forms the well-known Moa iron ores [LEITH and MEAD, 1911; CUMINGS and MILLER, 1911]. Renewed activity along the earlier axis in late Tertiary or Quaternary time raised this surface into a pronounced dome. The north flank, however, was submerged slightly, so that laterite extends out under Moa Bay. Active coral reefs have been built up, behind which the enclosed bays, protected from wave and current action, are filling up with coral sand and land-derived detrital material. Cayos Moa and Burro are low accumulations of coral sand raised a few feet above sea level.

Topography, climate, and vegetation--The outstanding physiographic feature of the Moa district is the laterite-covered, domed surface already mentioned. This slopes upward at a gradient of three to four degrees from the coast to an altitude of nearly 3000 feet near the crest of the range. Isolated hills, monadnocks on the old surface, rise a few hundred feet higher to form the irregular peaks along the main divide. The rapid headward erosion of a number of streams, which have cut deep, V-shaped valleys, has destroyed part of the surface, but extensive areas of laterite remain on the broad divides between them. The broad uplift which, as THAYER [1942 a, p. 57] has pointed out, causes the bulge of the coast from Baracoa to a point west of Moa, was apparently modified here by a local dome, for both the Rio Moa and the Rio Jiguaní curve inward as though around its flanks. The upper course of the Rio Moa was determined by the overlying sediments, which still occur a short distance to the west.

The climate is humid. The prevailing northeast trade winds precipitate their moisture as they strike the mountainous coast, and rainfall averages about 60 inches, distributed nearly evenly throughout the year. In contrast to most areas underlain by serpentine, the district is covered by a dense growth of vegetation, apparently made possible by the heavy rains and the deep laterite mantle, which ranges in thickness from a few feet to about 80 feet, except where it has been removed by erosion. Pine predominates on the laterite-covered surface, particularly at lower altitudes, and various hardwoods grow along the valleys and in the higher parts of the district. Exposures are common only on the sides and in the bottoms of the valleys, but the steepness of the slopes, often 50 degrees or more, and the dense underbrush make geologic work extremely difficult except in cleared areas along roads and near the mines.

Mining history--Chromite bodies crop out on the canyon walls at a few places, and float from them is abundant and noticeable in the streams below. The earliest mining denouncements (claims) were made late in the last century and early in this on the deposits of the Cayoguán group, which straddle the Rio Cayoguán four miles above its mouth, and on the Potosí and other deposits on Arroyo Saltadero, tributary of the Rio Yamanigüey. In the first decade of the present century the laterites were recognized as potential iron ore and the entire district was quickly staked for this metal. Some chromite deposits have since been found within these denouncements.

Except for a brief period during World War I the chromite deposits of the district had not been exploited until 1940, when the present mining activity began. Since that time exploration and development work have been undertaken on most of the known bodies and a number of them have been exhausted. Production has amounted to about 500,000 long tons. As known reserves are on the order of 250,000 long tons, and it is probable that much ore remains to be discovered, the district is one of the most important in Cuba. The ore is of refractory grade, averaging about 36 per cent Cr_2O_3, 28 per cent Al_2O_3, and less than three per cent SiO_2, has satisfactory physical qualities, and has been one of the principal sources of this type of chromite during the war years.

Previous investigations and field work--Prior to 1941 the only investigations of the chromite deposits were rapid reconnaissance trips made by Burch, BURCHARD [1919], and D. F. Hewett during and soon after the first World War. In the winter of 1940-41 W. D. Johnston, Jr., and T. P. Thayer examined the mines of the Cayogúan group, and the latter made tape and compass surveys of the most promising deposits [THAYER, 1942 a, pp. 66-71, pls. 19-20].

The writer joined Thayer in Cuba in January, 1942, and spent most of the following three years in field work in this and the other chromite-bearing districts of the island. The work was a part of the program of mineral investigations carried out in the American Republics by the United States Geological Survey under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation with funds transferred from the Department of State and the Foreign Economic Administration.

No satisfactory base map of the district is available, as standard topographic mapping has not been done. In 1942 the United States Army Air Forces took Trimetrogon aerial photographs of the district in the course of their mapping project for eastern Cuba, which were compiled in Washington by the Geological Survey, Alaskan Branch, on a scale of 1:80,000 and published for limited distribution at 1:500,000. Additional strips, flown in 1944, have been used by the author to supplement the detail of the original compilation. The plane table and telescopic alidade were used in mapping the Cayoguan group and the various mines.

The ultramafic complex

Rock types--The serpentine massif of the district is, as in Camagüey [FLINT, DE ALBEAR, and GUILD, in press] and other parts of Cuba, composed for the most part of peridotite with minor quantities of dunite, chromitite, and pyroxenite, and of the feldspathic rocks gabbro, troctolite, and anorthosite. Gradations occur from one type to another according to the relative proportions of the constituent minerals olivine, pyroxene, plagioclase feldspar, and chromite, but pyroxene and chromite are seldom found together. Partial to almost complete serpentinization of the ultramafic rocks and alteration of the feldspathic rocks to chalky aggregates of a number of hydrous minerals, including antigorite (?), zoisite, edenite, chlorite, and zeolites, are common.

The peridotite is a medium-grained, equigranular rock made up originally of olivine and pyroxene with little or no accessory chromite, which has been partly altered to the serpentinous minerals antigorite, chrysotile, and bastite. It is dark green to almost black on fresh surfaces and greenish-gray on the polished surfaces of boulders and stream beds, but where chemical decomposition has been predominant it weathers to a rusty brown, somewhat porous mass of limonite in which the pyroxene grains stand in slight relief. A concentration of the pyroxene along parallel layers, each a few millimeters thick and separated from the next by an equal thickness of pyroxene-poor material, gives the rock a rude gneissic structure or foliation which is ordinarily not distinguishable on fresh surfaces.

The primary constituents, before alteration, were five to 50 per cent of orthorhombic pyroxene and 95 to 50 per cent of olivine; in the average rock these figures are about 25 and 75 per cent, respectively. Because of the orthorhombic nature of the pyroxene the peridotite belongs to the variety harzburgite or saxonite. The olivine is highly magnesian, containing about 92 per cent of the forsterite molecule Mg_2SiO_4. Measurement of the refractive index and optic angle of the pyroxene indicates that it is enstatite with the approximate composition $En_{90}Of_{10}$, or that the molecular ratio of Mg to Fe is 9/1. A conspicuous feature of the pyroxene is the presence of extremely regular thin lamellae of a monoclinic pyroxene, believed to be diopside, which appear as fine striae under crossed nicols (see Fig. 3). The lamellae are a few thousandths of a millimeter thick, are oriented parallel to the optic plane (010), of the host, and extinguish at an angle of approximately 42 degrees to their trace. The c axes coincide, and the a axis of the diopside is parallel to the b axis of the orthopyroxene. HESS and PHILLIPS [1938] point out that this type of intergrowth is common in the orthopyroxenes of many peridotites, and ascribe it to exsolution on cooling of calcic pyroxene held in solution at higher temperatures.

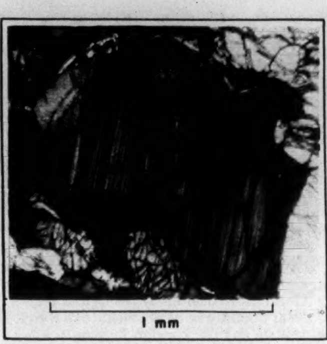


Fig. 3--Diopside lamellae (bright lines) in enstatite; grains with high relief are olivine; crossed nicols

The degree of alteration varies considerably from place to place; in general it is greater in sheared than in unsheared rock. Olivine is more susceptible than pyroxene, and pyroxene grains may be fairly fresh even where the olivine has entirely altered to antigorite. The olivine is attacked first along intersecting fractures, being replaced by a felted mass of antigorite and magnetite. In places the process reached completion, but in most thin sections small residual cores of olivine remain which show the general outlines of the original crystals by their simultaneous extinction under crossed nicols. Cross-fibered chrysotile veinlets from 0.1 to one millimeter thick, flanked by narrow zones of complete alteration, follow minute fractures in the rock. Two processes have affected the pyroxene: (1) Alteration to an amphibole, apparently anthophyllite or cummingtonite, which starts in along the diopside lamellae from crush zones through the mineral; and (2) alteration to bastite adjacent to some of the chrysotile veinlets. In general, however, the pyroxene is moderately fresh even where the olivine is completely serpentinized. Olivine grains in the pyroxene-rich layers are less altered than in the olivine-rich layers, and as there is evidence that serpentine is a stress mineral, it is suggested that where the pyroxene grains touch and are mutually supporting they protected the interstitial olivine from stress.

Peridotite grades into dunite through decrease in the pyroxene content, dunite containing 95 per cent or more of olivine. In the Moa district, however, the boundaries between the two types are ordinarily sharp, and an abrupt transition occurs from dunite with no pyroxene to normal peridotite. Because of the lack of pyroxene the dunite weathers smoothly to a limonitic surface on which only scattered grains of chromite, a millimeter or less in diameter, and small chrysotile veinlets stand in relief.

The rock is medium-grained and allotriomorphic. Anhedral to subhedral chromite grains, in most places constituting less than one per cent of the rock, are present almost everywhere. Alteration of the olivine to antigorite and magnetite is commonly 50 to 90 per cent complete.

The dunite occurs most conspicuously in close association with chromite, both as narrow envelopes surrounding the deposits and as dikes cutting through them. This relationship has been observed in many parts of the world, and Thayer, in a personal communication, suggests that the lack of pyroxene adjacent to chromite may be due to its instability at high temperature in the presence of a spinellid mineral. In addition to the envelopes, which range from less than a foot to several dozen feet in thickness, and the dikes, ordinarily a foot or less thick, dunite also occurs as layers and small masses within the peridotite, unassociated with any known ore deposits.

No true pyroxenite is known in the Moa district. A few dikes with gabbroic affinities have so little feldspar that they might be termed pyroxenites, and were so regarded in the field, but it is preferable to include them with the feldspathic rocks.

The ore deposits display most of the features of the silicate rocks, and are so clearly the result of early segregation that the term "chromitite," referring to their high content of chromite, is applied to them here. Chromite is a hard, black oxide, belonging to the spinel group and having the general composition $(Mg, Fe)O \cdot (Cr, Al, Fe)_2O_3$, which, as THAYER [1946] has shown, reflects the overall composition of the magma from which it has formed. The chromites of the deposits in the Franklyn, Cayoguán group, Delta, and Potosí zone (see Fig. 2) are very similar chemically, as is also ore from the Varias Aguas prospects (see Table 1). The Varisaguas ore, on the other hand, is much lower in chromic oxide, and as the iron content is about the same as in the other deposits, alumina must be high. This and the El Cerro deposit have not been visited by the author. According to THAYER [1942 b], however, the country rock is gabbroic, and the deposits display more similarity to those of the nearby Sagua de Tánamo district with which he grouped them than to those of the Moa district in which they fall geographically.

Table 1--Composition of some chromites[a] of the Moa district, Cuba
[R. E. Stevens and M. K. Carron, analysts]

Item	Cayoguán	Narciso	Potosí	Delta No. 1 (partial analysis)	Varias Aguas (partial analysis)	Varisaguas (partial analysis)
	pct	pct	pct	pct	pct	pct
Cr_2O_3	38.03	38.26	39.62	38.84	38.93	27.45
Al_2O_3	30.96	30.30	24.96	...	...	...
$Fe_2O_3{}^b$	2.59	2.55	5.21	11.39[c]	12.87[c]	12.56[c]
FeO^b	10.36	10.84	14.00			
MgO	17.43	17.22	14.60	...	...	...
MnO	0.03	0.09	0.15	...	...	...
CaO	0.02	0.30	0.20	...	...	...
TiO_2	0.06	0.19	0.44	...	...	...
SiO_2	0.24	0.52	0.80	...	...	...
H_2O +	0.10	0.12	0.02	...	...	...
H_2O -	none	none	none	...	...	...
P_2O_5	0.06	0.06	...	...	...	...
S	none	trace	...	...	...	...
Total	99.88	100.45	100.06	...	...	...
Ratio Cr/Fe	2.64	2.56	1.86	2.34	2.07	1.49

[a] Cleaned of nearly all silicate impurities
[b] Calculated to give one-to-one ratio of RO to R_2O_3
[c] Total iron as Fe

The concentration of chromite in the ore varies widely; the best deposits contain only a few per cent of gangue minerals, whereas in some the chromite is subordinate to the silicates. The average ore of the district contains about five per cent of silicates by weight. The common gangue minerals are serpentinized olivine and alteration products after calcic plagioclase feldspar. The low-grade ores consist of individual grains of chromite, usually anhedral, disseminated in dunite. Grain size ranges from less than one to a few millimeters, in general increasing in the richer ores. The high-grade ores which form the bulk of the known deposits appear almost massive, with only minor amounts of silicates interstitial to the chromite grains (see Fig. 4). The texture is medium- to coarse-grained inequigranular. Most grains are only a few millimeters in diameter, but a few are measured in centimeters, and one six inches across was seen. The individual grains interlock to some extent in most places where silicates are scarce, so that the ore is moderately cohesive, but in a few places where the grains are subhedral to euhedral a silicate bond is lacking and the ore is extremely friable. The octahedral habit is the usual one in euhedral ore; in a few crystals, however, the octahedron is beveled by dodecahedral faces. Nodular ore is not common, but is present at the margins of a few deposits. A peculiar reverse-nodular texture of spherical masses of olivine an inch or two across in otherwise massive chromite occurred in the southern part of the Cayoguán ore body.

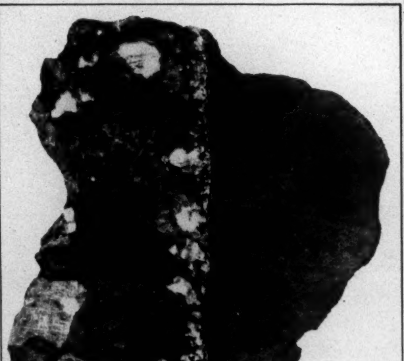


Fig. 4--Polished specimen of massive chromite and coarse pegmatite from Cayoguán mine; scale in inches

Although chromite is not easily susceptible to alteration under ordinary conditions, it is subject to limited attack at high temperature. A pale green chlorite has replaced euhedral chromite, leaving only skeletal outlines of many of the crystals, in a small deposit on the Narciso

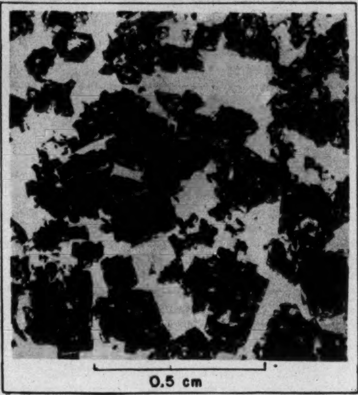


Fig. 5--Chromite, black, attacked and replaced by pale cholrite, white. Note numerous crystal outlines. Narciso denouncement

denouncement (see Fig. 5). Kammererite, the pink chrome-bearing chlorite, occurs sparingly as thin films coating grains or filling narrow fissures in the ore in many deposits, and the question may be raised as to why the green chlorite of Figure 5 is not also chromiferous. Apparently chromium ions are quite mobile under certain conditions and capable of moving appreciable distances. The monoclinic pyroxene of a gabbro-filled breccia zone at Delta No. 2 deposit has bright grass-green borders where it is in contact with the chromite, presumably because of a small content of chromic oxide derived from the ore. Brilliant green grains of uvarovite, the calcium-chrome garnet, are associated with the chromiferous pyroxene as reaction rims between it and the chromite. Elsewhere uvarovite-covered joint surfaces in ore are both common and extremely spectacular, as the green contrasts strongly with the black chromite. The refractive index of the garnet is about 1.76, indicating a composition of about 15 per cent of the uvarovite (chromian) and 85 per cent of the grossularite (aluminian) molecules, respectively.

The chromite deposits are commonly tabular or lenticular, with two dimensions considerably greater than the third. They range in size from thin streaks a few feet long and less than an inch thick to masses hundreds of feet long and many tens of feet thick. Dimensions of the larger deposits are shown in Table 2.

Table 2--Greatest known dimensions of some deposits of the Moa district

Deposit	Strike length	Dip length[a]	Thickness
	ft	ft	ft
Cayoguan	320	700	90
Narciso-Cromita	450	200	60
Cromita No. 3	150	100	28
Delta No. 1	250	300	50
Delta No. 2	250	60	30
Franklyn	65	50	45

[a] Remaining after erosion of part of the deposit.

Contacts are quite sharp in most deposits, presenting no problem of an "assay boundary" in mining. A slight tendency toward layering is developed at the margins of some deposits, however, with alternating parallel layers of varying silicate content in which the proportion of chromite decreases outward from the deposit to the country rock. An outstanding example of this was exposed at the upper contact of the Cayoguán deposit on the 535-foot level, where the upper four feet of ore was composed of alternate layers of massive chromite and medium- to fine-grained chromite disseminated in serpentinized dunite. Some small deposits have no massive ore, but are composed entirely of layered material.

Fault contacts are perhaps more common than primary igneous contacts, and where present they provide good walls to which to mine. The Franklyn body, the only notably equidimensional deposit in the district, was completely blocked out by faults, and may have been derived from a larger, less equidimensional mass now removed by erosion. Faults often more or less follow primary contacts, smoothing off irregularities and removing the dunite envelopes so that ore lies in contact with peridotite. The association of dunite with chromite is so universal wherever primary contacts have been observed that the presence of peridotite adjacent to ore in a diamond-drill core strongly indicates a fault contact.

With the exception of the small deposits at the west edge of the district the known ore bodies are restricted to a narrow belt trending nearly west from the Potosí group to the Franklyn mine.

This distribution does not seem to be due to the accident of discovery, for although chromite float is very persistent and can easily be traced to its source, no trace of it has been found in any of the numerous road cuts and valleys. It is unlikely, therefore, that any large deposits crop out between this zone and the coast. Prospecting in the more remote areas has not been so thorough, but here also no chromite float has been found in any of the stream gravels. In contrast to this, known deposits are numerous along the Potosí-Franklyn zone where the streams have removed the laterite mantle. The valleys of Rios Yagrumaje and Moa, along the line connecting the Franklyn and the Cayogúan mines, appear to be the most favorable areas for future prospecting.

Feldspathic rocks are closely associated with the complex, being in part contemporaneous and gradational with and in part intrusive into the ultramafic members. Masses with gradational contacts range from narrow layers in peridotite and chromite to bodies of considerable size, whereas the intrusive dikes which cut peridotite, dunite, and chromite are narrow and sharp-walled. A dikelike mass with gradational contacts to the enclosing rocks appears to be a transition form between the two types.

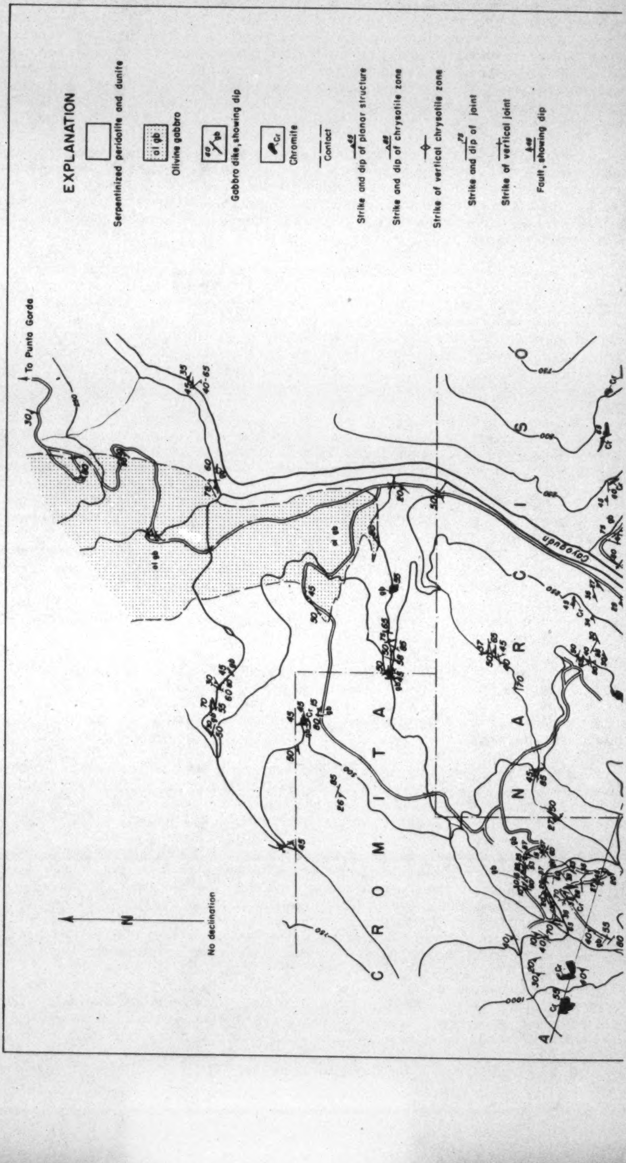
The essential minerals of the feldspathic rocks are calcic plagioclase feldspar, orthorhombic and monoclinic pyroxenes, and olivine. Chromite and magnetite are occasionally present as accessory minerals. Probably the most common rock is an olivine gabbro containing approximately equal proportions of bytownite and the mafic minerals augite and olivine, but all variations are found from rocks containing almost no feldspar to those with little if any dark constituents. Textures range from medium-grained equigranular to extremely coarse-grained pegmatitic. The feldspathic rocks are, therefore, much more variable than the ultramafic rocks in both composition and texture, and only the more common and important type will be discussed here.

The least feldspathic phase of the irregular masses is simply peridotite with small clots of feldspar, usually flattened and aligned in layers, interstitial to the pyroxene and olivine. The composition changes rapidly normal to the layers, and in most places this rock is only a gradational contact facies of a larger mass of olivine gabbro. The border zone of the olivine gabbro mass at the north edge of the Cayogúan group (see Fig. 6) is well exposed in the stream bed 400 feet north of the Narciso boundary and at the bend of the river 1500 feet north of this boundary. The main body, although designated as olivine gabbro, is of variable composition, being in part troctolite and in part anorthosite. The feldspar is consistently calcic, ranging from about An_{80} to An_{95} and averaging close to An_{85}. Anhedral to occasionally subhedral olivine is the predominant mafic mineral in all but the most feldspathic facies. Augite is interstitial to the feldspar and olivine in some facies of the rock and is the only dark mineral in the anorthosite. Enstatite, though not so common, is also present in some places and complicated intergrowths of the two pyroxenes were seen in one thin section, where a large poikilitic augite grain rimmed the enstatite and penetrated it along both the front and basal pinacoids.

The development of poikilitic texture is very noticeable to the naked eye in a feldspathic body exposed along the road to the Delta mine, just east of the bridge across the Rio Cayogúan. Here individual crystals of augite an inch or more across enclose numerous remnants of the original rock, a rather fine-grained mixture of olivine with minor enstatite and perhaps 15 per cent of interstitial feldspar.

The gabbroic dikes, in contrast to the irregular masses with gradational contacts discussed above, are narrow, sharp-walled bodies which fill fractures in the peridotite, dunite, and chromitite. They commonly range in width from less than an inch to a few feet, and have lengths up to at least several dozen feet. Dikes in peridotite are for the most part constant in strike and dip for as far as they can be traced; one thin one follows joints of two sets alternately, however, making sharp turns from one to the other. Dikes cutting ore split, or branch out around blocks of chromite, and the wider ones contain angular fragments which in some places are so numerous as to constitute a breccia of ore cemented by gabbro. That the fragments did not sink to the floors of the dikes, but are found in all parts of them, indicates a considerable viscosity for the magma at the time of intrusion. The dikes are relatively far more numerous in chromitite than in peridodite, for whereas they make up only an insignificant fraction of the total mass, they are so common in the ore as to present a real problem in mining, and may bulk ten per cent of a deposit.

The dikes have two strongly-contrasting textures. The normal rock is a medium- to coarse-grained granitoid aggregate of labradorite, near An_{60} in composition, and augite. Orthorhombic pyroxene and olivine may be present as minor constituents. Dikes in peridotite and some of those in ore show this texture, but many of those which cut the chromite are coarsely pegmatitic, consisting principally of feldspar and augite crystals measured in inches and even in feet. A dike exposed at the 450-foot level of the Cayogúan mine (see Figs. 7 and 8) shows both textures and gives


EXPLANATION
Serpentinized peridotite and dunite
ol gb
Olivine gabbro
Gabbro dike, showing dip
Chromite
Contact
Strike and dip of planar structure
Strike and dip of chrysotile zone
Strike of vertical chrysotile zone
Strike and dip of joint
Strike of vertical joint
Fault, showing dip
To Punta Gorda
No declination
N
CROMITA
NARCISO
Cayoguán
ol gb
A

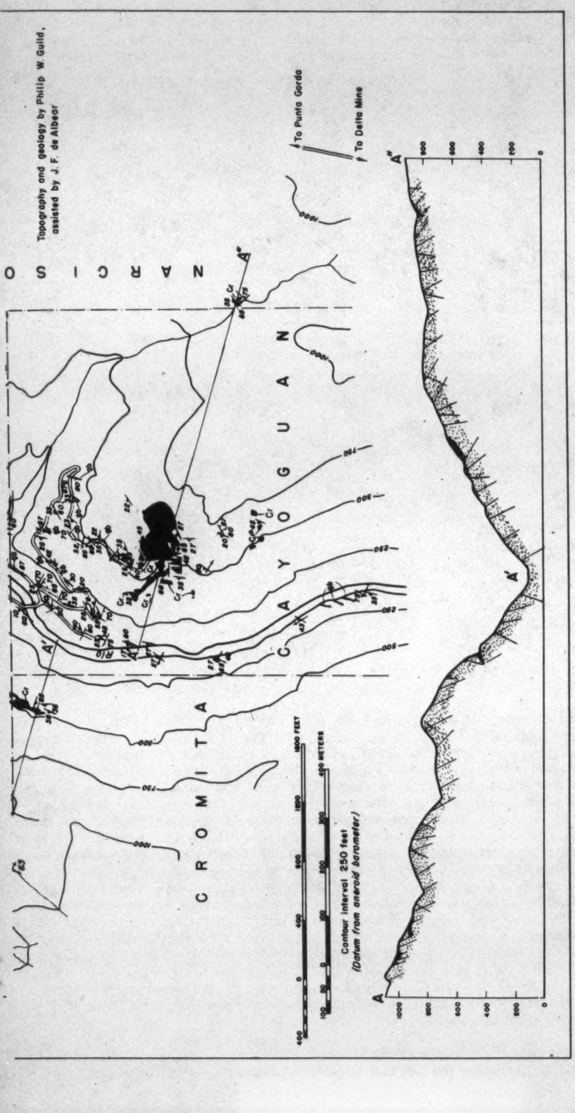

Topography and geology by Philip W. Guild, assisted by J. F. de Albear
NARCISO
CAYOGUAN
CROMITA
To Punta Gorda
To Delta Mine
Rio
Cr
A
A'
A''
1000
750
500
250
Contour interval 250 feet
(Datum from aneroid barometer)
400 0 400 800 1200 1600 FEET
100 50 0 100 200 300 400 500 METERS
1000
800
600
400
200
0

Fig. 6--Map and section of the Cayoguán group, Moa district, Oriente Province, Cuba a clue to the relation between the two types. Most of the rock is a pegmatite of augite crystals a foot or more long, extending nearly from wall to wall across the dike, with coarse single crystals of plagioclase filling the spaces between them. Part of the dike, however, consists of irregular patches of medium-grained gabbro which are unreplaced remnants of the original material.

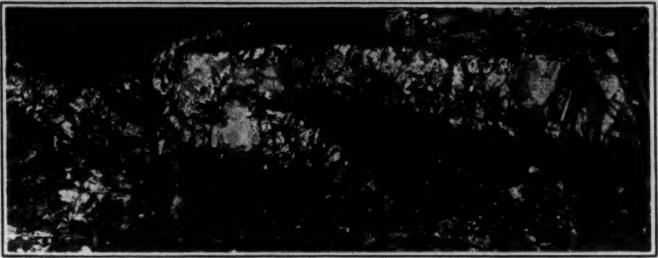


Fig. 7--Gabbro pegmatite dike cutting chromite on 450-foot level, Cayoguán mine; hammer indicates scale

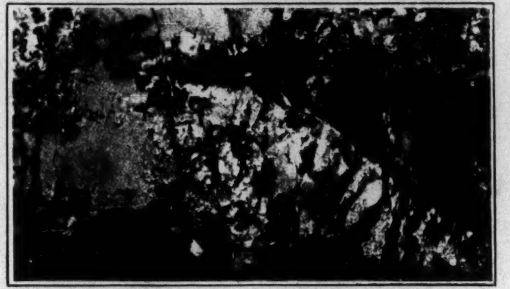


Fig. 8--Close-up of dike shown in Figure 7; normal-textured gabbro at left, coarse augite and plagioclase crystals at right

Under the microscope numerous reaction phenomena are seen in the edges of the large crystals where they encroach on the normal-textured rock. The border zones of some feldspar crystals are filled with small subhedral grains of augite, in part with enstatite rims against the feldspar, and olivine, which is far more abundant here than in the material being replaced. The feldspar is about An_{70}, considerably more calcic than the original mineral (An_{60}), and has still more calcic rims against the augite, suggesting that it has abstracted lime from the augite molecule. The rims on the augite apparently are caused by complete removal of lime and alumina from this mineral, leaving only magnesia, iron, and silica to form enstatite. Although no evidence was seen of replacement of enstatite by olivine, the abundance of the latter mineral in the border zones may perhaps be caused by the further desilication of pyroxene during the formation of the large feldspar crystals. The secondary augites also have a poikilitic habit at their contacts with the unreplaced rock, enclosing and replacing the original feldspar and augite and forming enstatite rims on the olivine. Where the augite and feldspar border zones meet, the feldspar apparently prevails, replacing the most advanced extremities of the augite and in some places maintaining its crystal outline at the other mineral's expense. The original small augite grains are black and highly magnetic because of close-packed inclusions of magnetite, ordinarily somewhat elongated and oriented parallel to the 010 plane of the host. The large augites tend to reject the magnetite, which coalesces into irregular masses interstitial to the silicate minerals, while the augite itself is light to dark green and not noticeably magnetic.

The end result of this process of replacement is shown in Figure 4. The right half of the specimen is nearly massive chromite; the left half is gabbroic pegmatite with a relatively fine-grained selvage against the ore. This selvage is not a regular feature of the dikes, and as often as not is lacking. The feldspar is gray where fresh, and dead white where alteration has set in. Crystal faces are visible at the lower left corner, in the small lozenge-shaped crystal enclosed in augite above the figure 3 on the scale, and elsewhere. The augite crystals are black to gray and show the trace of the prismatic cleavages as fine parallel lines. There is a decided tendency toward orientation normal to the wall. Coarse magnetite is interstitial to the augite near the center and at the top of the specimen, and other patches, too small to show in the photograph, are visible in the specimen. At the bottom, just above 3.8 of the rule, a tiny offshoot from the dike penetrates chromite; the main contact is at 3.5.

The coarsest texture found occurred in another dike in the Cayoguán deposit (see Fig. 9), where the upper three feet of a four-foot dike was composed of single augites set perpendicular to the contact, with minor feldspar filling the interstices. The footwall zone contained coarse, unoriented augites.

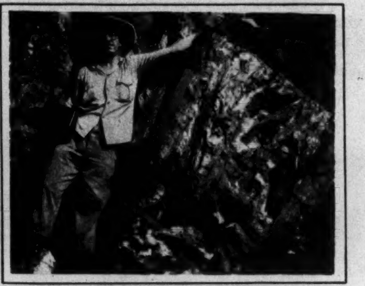


Fig. 9--Coarse pegmatite dike composed principally of augite crystals oriented normal to the walls; note sharp contacts against ore; 535-foot level, Cayoguán mine; rod divided in feet

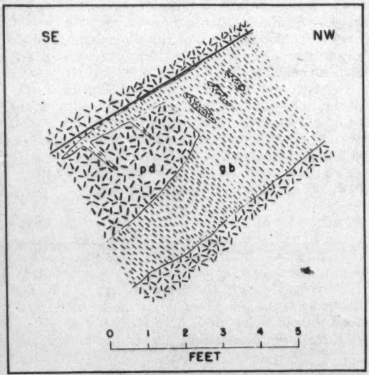


Fig. 10--Diagrammatic sketch of a gabbro "dike," gb, which has intruded and replaced peridotite, pd; thin line indicates gradational contact, heavy line is a fault; Cayoguán mine road

A gabbro mass transitional between the irregular bodies and the dikes is exposed on the Cayoguán mine road about where it crosses the 250-foot contour (see Fig. 10). Although it has the general shape of a dike, the contacts are irregular and gradational in detail, and the texture suggests replacement of part of the original constituents of the peridotite, rather than the injection of entirely new material. The predominant mafic mineral is olivine instead of augite, as in normal dikes, replaced to a considerable degree by felted aggregates of chlorite. Minor augite occurs both as rims on olivine and as individual grains. The feldspar is completely altered to a chalky white, semi-opaque mass consisting of serpentine, calcite, and a colorless amphibole believed to be edenite.

The pattern of "dikelets" penetrating the peridotite mass at the left edge of the sketch and the three small remnants of this rock to the right indicate stoping and digestion by feldspar-forming solutions which followed and spread out from planar structures in the original rock. As will be discussed later, the principal, southeastward-dipping direction is that of a joint set, and the northwestward-dipping direction is that of the foliation of the peridotite. The mafic constituents have a pronounced planar orientation, indicated by the dashes, parallel to the foliation of the replaced rock, and the mass is, therefore, discordant and conformable. A post-gabbro fault closely follows the upper contact, but leaves a narrow slice of peridotite between the contact and the fault along most of the exposure figured.

Other irregular masses, some with coarse knots of feldspar in what resembles an augen structure, also suggest that partial replacement of ultramafic rocks played an important role in the development of some of the feldspathic rocks of the district, particularly of those closely associated with the ore deposits.

In general the degree of alteration of the feldspathic rocks varies with the proportion of mafic constituents. In the feldspathic peridotites the feldspar is completely replaced by a chalky white aggregate of grains too small to be identified satisfactorily by optical methods alone. The refractive index of the most abundant mineral is about 1.56. Differential thermal analysis [HENDRICKS and ALEXANDER, 1939] of a sample of this material showed that it is composed chiefly of a serpentine mineral which, from its flaky, non-fibrous habit, is probably antigorite. A pale monoclinic amphibole occurring in scattered crystals is believed to be edenite. Varying amounts of calcite are present. The plagioclase is completely gone even though the olivine may be relatively fresh. As the mafic minerals decrease the feldspar becomes less altered until in the normal rock it is quite fresh. Serpentinization of the olivine also decreases, but not to the same extent. The pyroxenes are ordinarily fresh.

The feldspar of the dikes is also more or less altered to serpentine, edenite (?), at least two zeolites which may be chabazite and thompsonite, zoisite, and probably some other minerals. Veinlets of clinozoisite are common. Minor elements, presumably present in the original silicates, have been concentrated in the alteration products in a few places. Small crystals of thulite, the pink manganese-bearing zoisite, were seen in an altered dike at the Cayoguan mine. In other dikes, veinlets and indistinct zones of a bluish green, waxy-appearing mineral which is probably garnierite, as it gives a positive qualitative reaction for nickel, are concentrated in the altered feldspar around remnants of decomposed pyroxene crystals.

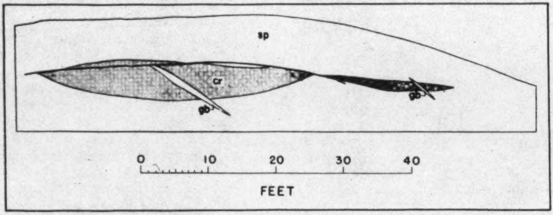


Fig. 11--Sketch showing lenticular gabbroic dikes, gb, cutting chromite, cr, and pinching out in serpentinized peridotite, sp

The areal distribution of the feldspathic rocks is not well known, as mapping is far from complete, but there does not seem to be a regular pattern as in the Camagüey district, where the gabbro and troctolite overlie a chromite-rich zone at the top of a rudely stratiform complex. However, although a spatial relationship between the large irregular gabbroic masses and the ore deposits cannot be demonstrated, the dikes show a very decided preference for the deposits, probably in part because the chromite solidified first and was more capable of holding open fractures at the high temperatures prevailing during the gabbro stage. The lenticular shapes of dikes in narrow bodies bear this out. Two dikes (see Fig. 11), formerly exposed in a small deposit on the Narciso denouncement, taper toward the contacts of the ore with serpentine, and pinch out quickly in the country rock. The dike to the left terminates against a fault which more or less follows the upper contact of the lens over part of its length before cutting through it as shown in the sketch. In the larger ore deposits dikes cannot so easily be traced from wall to wall, as it is rare for much of a deposit to be exposed at any one time, but no dikes are known to persist for more than a short distance into the serpentine, and most of them are localized completely in ore.

Structure--As the ultramafic complex of the Moa district has not been subjected to the extreme deformation which has affected serpentine areas in western Oriente and Camagüey provinces, but has only been arched into a broad dome, the internal structures of the mass have been well preserved, in contrast with those areas in which severe shearing and complete serpentinization have destroyed nearly all traces of primary structures. Most of the observations to follow were made in the area of the Cayoguán group; preliminary studies in other parts of the district, however, suggest that the same relations will be found to hold there also. The attitudes of all structure elements measured during the course of the field work have been platted on the map of this group (see Fig. 6).

The most significant of these structures are the planar elements. Mineralogic variations in all rock types tend to be more rapid in one direction than in the other two; in other words, the rocks have a compositional layering, and outcrops commonly are banded. The most prominent layering is that of the chromite bodies themselves. These are tabular or lenticular and may have gradational zones near their borders of rapidly alternating chromite- and silicate-rich layers. The silicate mineral may be either serpentinized olivine or altered plagioclase feldspar, or both. Layering is not confined to the margins, but occurs also in the centers of even the largest deposits, as can be seen in Figure 12. Here feldspathic lenses from less than an inch to about three inches thick, with indistinct, gradational contacts to the massive chromite, are parallel to each other and to the contacts of the deposit dozens of feet above and below them. At the other extreme, with respect to size, are thin layers, some only one grain thick, of disseminated chromite, arranged in parallel layers in dunite.

Fig. 12--Feldspathic layers in massive chromite; 476-foot level, Cayoguán mine; thickest layer about three inches across

Dunite envelopes rim the chromite deposits, as has already been mentioned. These envelopes grade sharply into chromite on one side and into peridotite on the other, making a five-ply layering of peridotite, dunite, chromite, dunite, and peridotite which may be complicated by the addition of extra thin layers of feldspathic rock or dunite. The dunite envelope may vary gradually in thickness from a foot or less to several dozen feet, but in any one exposure the boundary with peridotite is essentially parallel to that against the ore.

Variations in pyroxene content within the peridotite also cause a layering, in some places of dunite and in others of pyroxene-rich rock. These layers are comparatively rare, as most of the peridotite is quite homogeneous in overall composition. A good example of dunite layers in low-pyroxene peridotite is shown in Figure 13, and of pyroxene-rich layers in normal peridotite in Figures 14 and 15.

The feldspathic rocks also display prominent layering in many places, through variation in the proportions of feldspar and mafic constituents (see Fig. 16). The centers of the larger feldspathic masses do not, however, show close-spaced regular layering, and it is probable that they are more or less structureless, although the few small exposures are insufficient for detailed observation.

A second planar structure, similar and parallel to the layering in most places but superimposed upon it, is the foliation of the peridotite. This structure is caused by the concentration of the pyroxene grains into somewhat flattened aggregates which are oriented parallel to one another, giving the rock a gneissic appearance (see Fig. 17). Although prominent on weathered outcrops, the foliation is difficult or impossible to find on fresh or polished surfaces, in contrast to the layering, which is always distinct.

Petrofabric analysis shows a tendency for the enstatite grains to be oriented with their 010 planes in the plane of the foliation. This orientation is revealed by the diopside lamellae (see Fig.

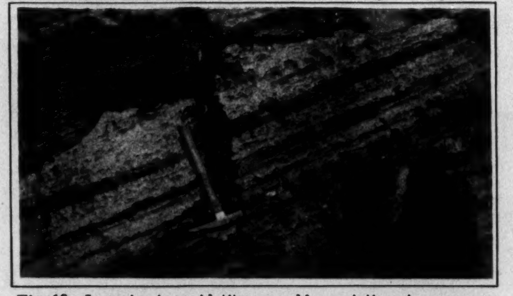


Fig. 13--Layering in peridotite caused by variations in pyroxene content; note solution along joints perpendicular to layers; east bank of Cayoguán river, 850 feet south of bridge

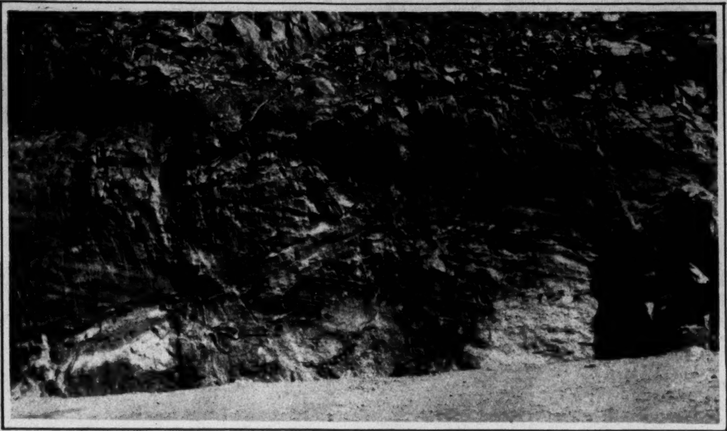


Fig. 14--Pyroxene-rich layers in peridotite, dipping gently to right. Note close-spaced, nearly vertical joints, and shear zones dipping to left; height of exposure about 15 feet. Cayoguán mine road, 150 feet east of bridge

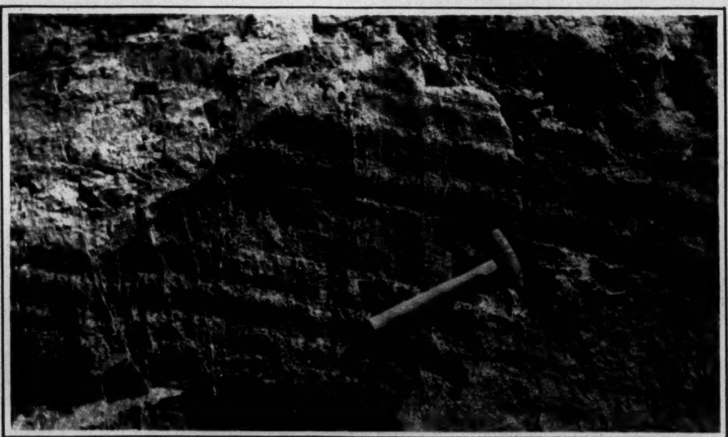


Fig. 15--Close-up of Figure 14; pyroxene-rich layers have weathered in slight relief; layering cut by foliation, parallel to hammer handle; vertical joints are filled with vein serpentine

3), which lie in (010) of the orthopyroxene, and therefore are themselves more or less parallel to the foliation. The pyroxenes of three mutually perpendicular thin sections of an oriented specimen of peridotite from the Cayoguán denouncement were studied on the universal stage. The procedure used is as follows: With nicols crossed, rotate the inner stage (A-1) until the enstatite is at extinction. If the lamellae are now visible they will either (1) be parallel to a cross hair, or

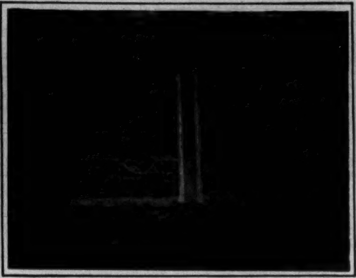


Fig. 16--Layering in olivine gabbro; the white layers are essentially anorthosite; boulder in Cayoguán river; scale approximately seven inches long

(2) make a small angle to a cross hair. If (1), tilt about whichever horizontal axis, N-S (A-2) or E-W (A-4), is parallel to their trace until they are at the sharpest position. For all cases except that in which a principal crystallographic axis of the enstatite is parallel to the stage axis about which the grain is turned, the enstatite will immediately brighten on being tilted. The sharpest position of the lamellae coincides with the extinction of the host mineral for these oblique sections. If (2), rotate on A-1 until the lamellae parallel a cross hair, and tilt on the axis parallel to this hair until extinction of the enstatite is restored, when the lamellae will be vertical. As the lamellae are only visible when they are not inclined more than 15 degrees to the axis of the microscope tube, they may not be immediately apparent. If not, tilt on A-2 or A-4 to various positions, rotating on A-1 to restore extinction of the enstatite. If the lamellae do not lie within 45 degrees of the plane of the thin section (in other words, are not at too low an angle to be brought vertical because of the limitations of the stage), they will become visible at some position by following this procedure. The one exception is for the basal section, on which both the lamellae and host extinguish together. For grains with this orientation it is necessary to tilt on both A-2 and A-4; fortunately they may be readily recognized from the cleavages.

The lamellae of each grain were measured, and their poles plotted on an equal-area net, separate sheets being used for each thin section. The point diagrams of two sections were then rotated to the plane of the third section, and the poles of all three combined, counted, and contoured. The composite diagram was then rotated to a horizontal plane.

The diagram (see Fig. 17d) shows two closely-associated seven per cent maxima, the larger of which is at the pole of the megascopic foliation. The lamellae, and (010) planes of the enstatites, therefore tend to lie in the plane of the foliation, indicating either that they grew in this direction, or were oriented in it by shearing stresses during the closing stages of intrusion and solidification of the complex.

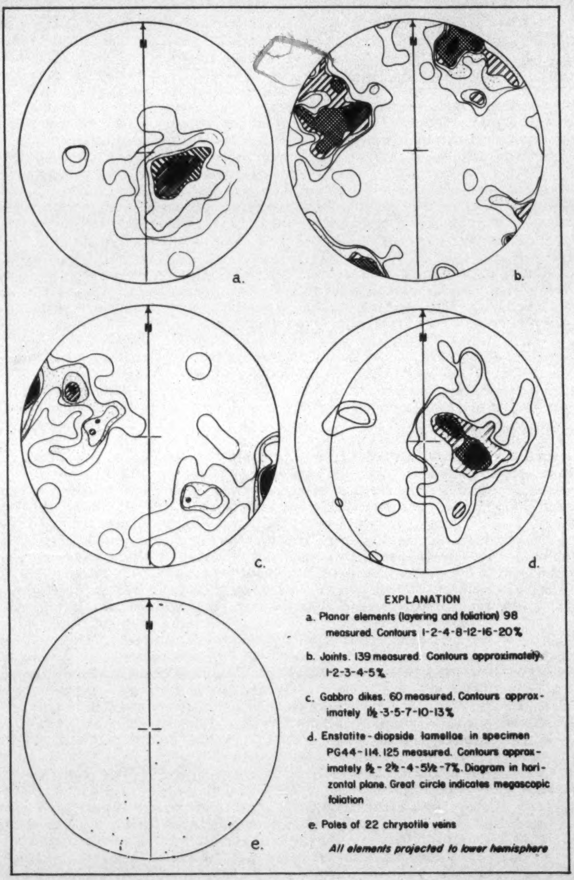
The foliation is parallel to the layering in almost all the exposures in which the two structures have been observed, and was not recognized as a distinct structure until the road cut shown in Figure 14 was made. In this exposure, however, the pyroxene-rich layers, which are here slightly arched and gently dipping, are transected at an angle of about 40 degrees by the foliation, faintly visible in Figure 15. The displacement of one of the pyroxene layers along the plane of the foliation (see Fig. 18) clearly indicates the age relations of the two planar structures, and the complete healing of the shear plane, which has left no trace other than the offset of the layer, is proof that the movement occurred before the final consolidation of the magma. The small faults at the left edge of the picture are healed with chrysotile veinlets and date from a later stage in the cooling of the intrusion. One of these veinlets crosses the foliation shear with no trace of offset.

In general the foliation is more constant in direction than the layering, and where only thin, relatively weak layers are involved in a local swirl, the foliation maintains its normal attitude as in the exposure just described. Where a strong, thick layer is involved, however, the attitude of the foliation is controlled by the layer. Thus in the southern half of the Cayoguán deposit, near the 500-foot contour, the ore displays a prominent roll and reversal of dip which is closely followed by both the dunite layer and the foliation of the peridotite. This and other deviations from the normal attitude near chromite are attributed to the influence of the ore masses in localizing stress.

The layers within the ultramafic members of the complex, and the thin feldspathic layers in ore and peridotite, are parallel to each other in all places where they have been observed. Except for small local variations, they strike slightly east of north in the southern part of the Cayoguán group, and swing around eastward in more or less concentric arcs toward the northern part of the area mapped. Dips are gentle to moderate to the west and north. The attitude of the compositional layering is best shown by the ore deposits. The Cayoguán, on the east side of the valley, lies nearly parallel to the hillside, while the Narciso and Cromita deposits across the river dip into the hill (see section, Fig. 6). The mining problems have quite naturally been more easily solved for Cayoguán than for the other deposits.

Layering within the irregular feldspathic bodies does not follow the general rule of parallelism, but instead seems to be controlled by the contacts of the mass itself. The 78-degree north-dipping planar structure at the bend of the river is the attitude of small elongated and oriented feldspar grains in peridotite in a gradational contact zone, while the ten-degree northwest-dipping structure at the road bend 600 feet north is the foliation of the peridotite, The two structures are not related. The few measurements of planar structures within this olivine-gabbro mass, as well as its general shape, indicate that it is intrusive into the peridotite, although at such an early stage that the peridotite itself was not yet completely solid.

The foliation of the peridotite is usually parallel to the layering, swinging around from north to east and dipping northwestward. Most of the readings plotted on the map were taken on this



EXPLANATION

a. Planar elements (layering and foliation) 98 measured. Contours 1-2-4-8-12-16-20%

b. Joints. 139 measured. Contours approximately 1-2-3-4-5%

c. Gabbro dikes. 60 measured. Contours approximately 1½-3-5-7-10-13%

d. Enstatite-diopside lamellae in specimen PG44-114. 125 measured. Contours approximately ½ - 2½ - 4 - 5½ - 7%. Diagram in horizontal plane. Great circle indicates megascopic foliation

e. Poles of 22 chrysotile veins

All elements projected to lower hemisphere

Fig. 17--Structure diagrams, Cayoguán group, Oriente Province, Cuba foliation, although it has not been distinguished from the layering by a different symbol. A statistical diagram (see Fig. 17a), constructed from 98 compass measurements of planar elements, shows a 20 per cent maximum near north 30° east, dip 30° northwest, which reflects, of course, the greater number of readings taken close to the line of section A-A″, where exposures are most numerous. Most of the other attitudes are grouped around this maximum.

The general trend of planar structures in other parts of the chromiferous zone is similar to that at the Cayoguán group, in so far as is known, except at the extreme western end. Foliation and ore at Delta No. 1 and No. 3 deposits strike north 10°-20° east and dip 30°-55° northwest, while at Delta No. 2, near the north edge of the zone, they strike about north 70° east, and dip rather steeply to the north, suggesting that the arcuate bend in the structures is present here also. At Potosí the foliation is north 45° east, 52° northwest. The nearby Tio Foli deposit strikes northeast and dips perhaps 60° northwest. The accurate mapping of these structures over the entire district is essential to a complete understanding of the intrusive history of the ultramafic complex, and should be one of the principal objectives of any future investigation.

Joints are prominent features of all outcrops of the ultramafic complex; it is probable that no volume of rock of more than a few cubic feet is without them. Exposures of the olivine gabbro mass are insufficient to determine whether it has any regular joint pattern, and the massive ore deposits are so complexly jointed that a systematic pattern is not readily apparent. Within the peridotite, however, two well-defined sets are recognized which bear a definite relationship to the planar structures and date from the closing stages of the igneous cycle. No such relationship can be demonstrated for other joints, apparently oriented at random; the latter may have resulted from stresses imposed at the time of the gentle doming of the complex.

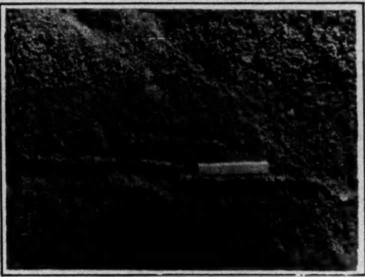


Fig. 18--Pyroxene layer offset along foliation, center of photo, and along nearly vertical joint system at left margin; about 25 feet north of Figure 15; scale approximately seven inches long

The most prominent joint set strikes approximately parallel to the strike of the foliation and dips at angles of 60 to 90 degrees to it. The usual relationship between these joints and the foliation is shown in Figures 19 and 20, where the foliation dips northwestward (to the right) and the joints dip rather steeply southeast. A conjugate set, with the acute angle in the upper left and lower right quadrants, substitutes for the joints of Figure 20 in some exposures, and both are present in a few places. The interval between the joints ranges from less than an inch to a few feet, and is usually less than one foot. The joints themselves have smooth, plane or gently-curved surfaces which in any one exposure are parallel to each other. Incipient joints of this set are revealed by solution in

Fig. 19--Joint sets in peridotite; cross joints dip to left, longitudinal joints face observer; height of exposure about ten feet; Cromita mine road, 1000 feet east of point A, Figure 6

Fig. 20--Close-up of Figure 19, showing relation of foliation, dipping to right, to the joint systems; a longitudinal joint, the front surface, and oblique joints, near hammer handle, were filled with vein serpentine

Figure 13, where it can be seen that they are more closely spaced, and solution has proceeded at a faster rate, in certain layers than in others.

These joints are here designated "cross joints" because they lie in or near a plane approximately normal to what is believed to have been the direction of intrusion of the rock. As elongate minerals are not present, however, there is no unmistakable evidence of the actual direction of flow, and this usage of the term is therefore not precise.

The average strike of the cross joints is north 20°-30° east; in general they are more constant in orientation than the foliation itself and do not seem to bend through as wide an arc as the latter structure, although the poor exposures in the northern part of the Cayoguan group do not permit the positive identification of the joint sets measured there, and some are probably oblique. The cross joints are most typically developed, and best exposed, in the vicinity of the deposits. They are shown diagrammatically in section A-A", Figure 6. A statistical analysis of the joints (see Fig. 17b) shows a pronounced maximum near north 30° east, dip 50° southeast, and a partial girdle in the vertical zone which extends through 90° to a dip of about 60° northwest.

Joints of a second, longitudinal set strike parallel with the direction of dip of the foliation and dip steeply, usually within 20 degrees of the vertical. They also are closely spaced and ordinarily separated by only a few inches or feet. They form the front faces of Figures 19 and 20; in the latter a characteristic filling of green vein serpentine, more resistant to chemical weathering than the altered peridotite, still covers part of the joint surface. The serpentine-filled veinlets visible in Figures 11 and 15 follow the longitudinal joints, which, like the cross-joints, are more regular in attitude than the foliation and do not swing with local variations of the latter structure.

The longitudinal joints cause a strong maximum at about north 70° west, vertical, on the joint diagram (see Fig. 17b).

In addition to the joints of the two sets described above, many others occur in all attitudes. These oblique joints do not ordinarily, however, have the regularity of spacing and orientation of the cross and longitudinal sets, although within a restricted area they may be so conspicuous as to overshadow them. A few oblique joints may be seen in Figures 14, 19, and 20; a close-spaced set in Figure 20 has been filled with serpentine.

Minor offsets along joints are common in the rocks of the ultramafic complex, but except where dikes or layers serve as markers the amount of movement cannot be measured. Dikes in peridotite have been offset a few inches or feet at many places; usually the continuations cannot be found, because of the poor exposures, and only a minimum figure for the displacement can be assigned.

The ore deposits have been so complexly faulted that it has not always been possible to reconstruct the original shapes and sizes, but in general the faults may be assigned to the same three classes as the joints. Faults roughly parallel to the cross joints have offset the contacts from a few feet to several dozen feet, as may be seen especially well at the Cayoguán mine. Strongly slickensided surfaces suggest that the two deposits at the western edge of the Cromita denouncement (near A) may be faulted parts of a single body; if so the displacement was on the order of 100 feet. Both normal and reverse faults are found, but the normal variety is more common, and the overall picture is that of tension in the direction of dip of the deposits.

The westernmost Cromita deposit is cut off on the north by a fault parallel to the longitudinal joints, as is also the south edge of the Cayoguán deposit over part of its length, and several faults with this attitude cut the southern end of the Narciso-Cromita ore body. Displacements in the last-mentioned deposit are nearly parallel with the dip of the upper contact, which therefore does not appear to be offset, but as the lower contact dips more gently the offsets do show up on it. The movement was perhaps five or ten feet on the faults at the Narciso-Cromita, but presumably was considerably greater at the other places, as the continuations of these deposits have not been found. The close-spaced faults with very small displacement which cut the pyroxene layer at the left edge of Figure 18 are also parallel to the direction of the longitudinal joint set.

Other faults which follow no discernible pattern are common in the ore deposits, and are seen in a few places in the peridotite. Most of them are simply slickensided surfaces which can be traced perhaps a few dozen feet before they split up and disappear, but a breccia zone at least 30 feet thick is exposed for 200 feet near the bend of the stream 700 feet northwest of the northeast corner of the Cromita denouncement. Rounded peridotite and dike fragments in sheared serpentine indicate strong crushing and considerable movement, and all traces of original structures are destroyed. The gentle eastward dip of the breccia zone suggests that it resulted from nearly horizontal compression of the complex at some period later than the intrusive stage and unrelated to it. Relief of stress along breccia zones of this type apparently protected the main bulk of the complex from strong internal shearing.

Although many joints are simply fractures in otherwise homogeneous rock, some have been filled with material of different composition, and a pronounced difference in the fracture fillings of the two regular sets provides significant clues to the time and manner of their formation.

Fig. 21--Zone of close-spaced, parallel chrysotile veinlets, white, in intensely serpentinized peridotite; normal peridotite on each side; Cayoguán mine road, bend 300 feet north of the deposit

The feldspathic dikes intruded into peridotite show a decided preference for the cross joints, as may be seen in Figure 17c. The greatest number, 13 per cent of the 60 observed, strike about north 25° east and are vertical, while most of the others have approximately the same strike but dip moderately to steeply southeast and northwest. Although the range of attitudes is somewhat greater than for the cross joints shown on Figure 17b, and the maxima of the two diagrams do not coincide exactly, a fair degree of correlation exists between them. The absence of any concentration of dikes in the direction of the longitudinal joints is conspicuous on the diagrams; examination of the map reveals, however, that in some places, particularly in the northern part of the area, a generalization based only on statistical data does not give an entirely accurate picture. Exposures both in the creek and on the road in the northeast corner of the Cromita denouncement show that the dikes tend to maintain their normal attitude even where the foliation has swung around 90 degrees to the southeast, so that they here follow a direction which by definition is that of the longitudinal joints. As already stated, exposures are insufficient in this area to explain this seeming irregularity, but it is supposed that the stresses which opened the joints and provided the channels for the injection of the gabbro were not influenced by local changes in the attitude of planar structures. It should be noted that in the next stream to the north the dikes once more follow the cross joints.

Within tne ore deposits the dikes are not only more numerous and coarser-grained, but they are not restricted to any particular joint set. Many of the faults have dikes along them; the dikes themselves may or may not be slickensided by renewed movement or offset by later faults. Because of the apparently random orientation of the dikes in ore and their great number, which would completely mask the strong preferred direction in the peridotite, they have not been included in the statistical diagram. This omission can be justified because conditions of rigidity at the time of formation of the dikes appear to have been so different for the ore and peridotite that a direct comparison cannot be made. As pointed out previously, the ore was capable of fracturing before the peridotite solidified, and thus may have been subjected to various stresses, probably during intrusion, which did not leave their mark on the still plastic or fluid silicate fraction of the magma.

Zones of a sort of "ribbon rock," consisting of parallel veinlets of cross-fibered chrysotile asbestos one to two millimeters thick, separated by two to three millimeters of intensely-serpentinized peridotite, are prominent features of the district. The zones range in thickness from an inch or less to about two feet, and may extend for dozens of feet. The contacts with the normal peridotite are sharp. A characteristic exposure of one of these zones is shown in Figure 21, and the sawed face of a specimen from this outcrop in Figure 22. In the latter figure individual veinlets are seen to lens, pinch, and fray out, but the overall pattern is maintained with marked regularity.

The olivine of the intervening peridotite septa is completely altered to antigorite, but the enstatite is relatively fresh. Minute octahedra and anhedral grains of magnetite, deposited along the cleavage of the olivine, preserve the original shapes of many grains and cause the rock to be noticeably magnetic. The dark zone near the right edge of Figure 22 is approximately 50 per cent magnetite by weight. Although magnetite is a common constituent of all the serpentine, no such concentration has been observed in the normal rock, and it seems certain that at least part of the iron has been introduced from elsewhere.

The distortion of enstatite grains cut by the chrysotile veinlets shows that the fractures were formed by sharply-localized shearing stresses (see Fig. 23). The bending of the diopside lamellae and the opening up of the pyroxene grain along minute gash fractures, now filled with chrysotile, are clear evidence of the forces exerted on the rock. Pyroxene grains not cut by these fractures show no sign of strain, and must have been protected by the more readily altered olivine. The chrysotile grew to some extent by replacement of the walls, but mainly by forcing them apart as it crystallized, since the edges of pyroxene grains cut obliquely by the veinlets are offset along the fibers, rather than aligned, as they would be if the veinlets grew entirely by replacement. The force necessary to separate the walls may have been very slight if the process of serpentinization was one which resulted in an overall decrease of specific volume, and the chrysotile might better be said to have grown by fissure filling. Shrinkage and filling apparently went on simultaneously and kept in pace with one another. There was virtually no movement on the shear planes, except for that necessary to distort the enstatites. Stress continued however, during the formation of the chrysotile and bent the fibers slightly along symmetrically-arranged intersecting planes which make angles of from 20 to 35 degrees to the walls of the veinlets. Under crossed nicols these show up as sharply-defined bright and dark bands crossing the veinlets; in plane light they are merely inconspicuous kinks in the fibers. The photograph (Fig. 23) was taken primarily to show distortion of the enstatite; strain lines in the veinlet do not show up as sharply as possible in this position. Although no fracturing occurred, the strain lines have preserved a graphic picture of the stresses under which the veinlets grew.

As can be seen in the structure diagram (see Fig. 17e), most of the chrysotile zones are approximately parallel to the longitudinal joint set. The longitudinal joints themselves are commonly filled with serpentine (see Figs. 15 and 20), and probably the only real difference between the joints and most of the zones lies in the development of multiple shears and intense serpentinization through some localization of stresses at certain places. Examination of the map (see Fig. 6) shows that nearly all these zones found lie relatively close to the ore deposits; this may be caused only by the better exposures in this area, but as outcrops along the Cayoguán River and the various streams are fairly good, there is a strong suggestion that the deposits themselves helped in this localization of stress. Additional evidence for this was the presence of such a zone along the fault bounding the south edge of the Cayoguán deposit, where the chrysotile was bonded tightly to the massive ore.

Origin of the ultramafic complex--The origin of the rocks and structures of the ultramafic complex involves many as yet unsolved problems of the differentiation, segregation, intrusion, and cooling under stress of sub-silicic ferromagnesian rocks, with the attendant alteration and replacement of some of the original minerals. Although many intrusions of this general class have been studied, each presents its own problems, and the writer knows of no exact parallel to the Moa district. The preservation of structures which may or may not have been present in other more highly

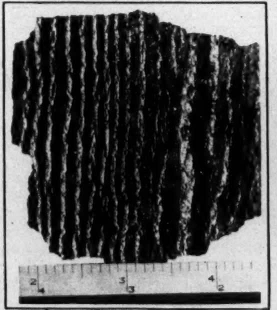


Fig. 22--Sawed face of specimen from chrysotile zone shown in Figure 21; white is chrysotile; foliation of original peridotite visible as faint bands dipping gently to left; scale in inches

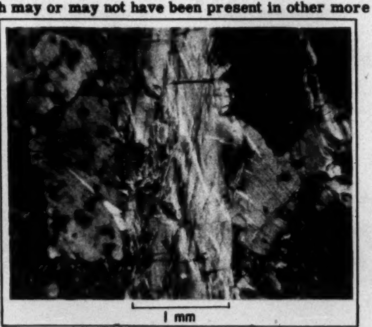


Fig. 23--Photomicrograph of chrysotile veinlet, showing distortion and offset of enstatite grain cut by veinlet; black lines in enstatite are diopside lamellae; the white wedges and lenses parallel to the lamellae are gash fractures filled with chrysotile; note the intersecting shear planes in the veinlet; crossed nicols deformed areas of peridotite gives clues to the mode of origin of the chromite deposits and of the ultramafic complex itself.

Certain salient features which should be explained by any theory of origin are the following: (1) Compositional layering of the peridotite, dunite, and chromitite; (2) foliation of the peridotite, parallel to the layering in most, but not all, places; (3) relation of the joint systems to the planar structures; (4) filling of the two principal joint systems with different materials; and (5) predominance of gabbro dikes in the ore deposits.

The key to the solution of the problem of origin is the chromitite. Various theories have been advanced for the formation of chromite deposits, according to their supposed relations to the enclosing silicate rocks. These are, briefly, that the chromite is the first mineral to crystallize [VOGT, 1894]; that it crystallized with or slightly later than the surrounding silicate minerals [SAMPSON, 1929]; and that in part it is one of the last minerals to form, being of the same period as the serpentine [FISHER, 1929]. Fisher and Sampson classify chromite deposits as belonging to the (1) early magmatic, (2) late magmatic, and (3) hydrothermal types.

Various chromite deposits investigated by personnel of the United States Geological Survey in recent years have been assigned to either type 1 or type 2. THAYER [1940, p. 94] states that fragmentation of nodular ore and the linear banding of some deposits in Grant County, Oregon, indicates that chromite crystallized before the end of the magmatic flowage of the enclosing dunite. RYNEARSON and WELLS [1944, p. 12] in discussing the origin of the Gray Eagle deposit, Glenn County, California, say: "The chromite crystallizing from the magma . . . appears to have accumulated to form bodies of chromite-rich dunite . . . The accumulation of the chromite-rich dunite probably took place before intrusion, and the clots of crystal mush moved as free units in the more liquid magma." THAYER [1942 a, pp. 26-27] has suggested that the Cuban deposits segregated at great depths and were "carried up as solid inclusions during the emplacement of the ultramafic rocks," a view with which the present writer is in accord. On the other hand, RYNEARSON and SMITH [1940, pp. 293-296] propose a late magmatic origin for the chromite deposits of the Seiad Quadrangle, Siskiyou County, California, which appear to have many points of similarity to the Moa deposits. The ore bodies are roughly tabular and parallel to a foliation of the peridotite. Individual layers are arranged in en echelon fashion. Two joint systems are present in places; one is normal to the foliation, which dips 37 degrees to 75 degrees, and the other is parallel to the dip of the foliation and dips steeply. Ore bands are folded. Deposits in the Del Puerto area, Stanislaus County, California [HAWKES, WELLS, and WHEELER, 1942, pp. 92-95] are ascribed to late magmatic ore-bearing solutions which penetrated fractures and breccia zones in peridotite.

That the chromite deposits of the Moa district are early magmatic is indicated by several features: (1) Deposits are entirely conformable with the compositional layering of the silicate rocks; (2) fractures in ore are filled by dunite dikes; (3) gabbro dikes in ore pinch and lens out as they enter peridotite, showing that the ore was relatively more competent than the peridotite at the gabbro stage; and (4) chromite layers influence the attitude of the foliation, which is parallel to the ore contacts even where the normal dips are reversed.

The writer believes that the chromite deposits are not only of early magmatic origin, but that the crystallization and segregation of the ore masses occurred prior to the emplacement of the complex in its present position in the Earth's crust, or, in other words, that the chromite bodies were already solidified at the time of intrusion. Features which have led to this belief are the following:

(1) The time available after the intrusion of a homogeneous magma seems insufficient for the growth and segregation of the coarse chromite crystals, especially as the compositional layers, including the chromite bodies, are known from the cross-cutting relation of the foliation to antedate final consolidation.

(2) Pyroxene grains were crystallizing and being oriented during the final stage of intrusion, at a temperature which must have been well below that for chromite. Nevertheless, the presence of dunite dikes shows that the ore was already rigid enough to fracture during the olivine stage, and the chromite deposits must therefore have been formed before the close of intrusion.

(3) Feldspar is present as a gangue mineral in deposits enclosed in completely feldspar-free dunite envelopes. This suggests either that the ore formed in a feldspathic environment which later was changed for a dunitic one, or that the feldspar formed by reaction between chromite and the surrounding liquid. The latter explanation is possible, but in either case it is probable that

the ore crystallized under different conditions of temperature than those obtaining at the time of final consolidation. Reaction between diopside and chromite at La Constancia mine, six miles east of the Moa district, has produced olivine and anorthite [THAYER, 1946, pp. 204-205]. Diopside forms below the temperature range in which this reaction should take place. The deposit must, therefore, have been heated up after the injection of gabbroic material into brecciated ore. This could occur through sinking to a deeper zone of the magma chamber, because of an influx of new magma, or by engulfment of the deposit by hotter material during some movement of the entire mass. The rarity of the phenomenon observed at La Constancia is probably due to the special combination of circumstances necessary to produce it. These are the juxtaposition of a lime-bearing pyroxene and chromite and the presence of sufficient heat to begin, but not complete, the reaction, since if it went to completion only olivine and anorthite, the usual silicate minerals which accompany the ore, would remain.

(4) The grouping of deposits in clusters along a relatively narrow zone down the approximate center of the intrusive mass suggests that the magma was already differentiated before intrusion, and that the material of this zone was derived from a part of the magma richer in chromite than the average.

(5) The parallel attitudes of the layering, and particularly of the ore bodies, are suggestive of the orientation of tabular masses during flow. If segregation occurred after intrusion, the writer can see no good explanation for the en echelon pattern of the deposits of the Cayoguán group, for example. On the other hand, if solid blocks of ore were dragged up along parallel courses during the intrusion of the complex, the present distribution appears quite logical. The similarity of the dimensions of the Cayoguán and Narciso-Cromita bodies suggests that they may be fragments of a single mass, broken during the intrusion and separated somewhat before consolidation. The almost identical analyses (see Table 1) of ore from the two deposits is also suggestive of this.

According to the hypothesis proposed here for the origin of the complex, the events which led to the development of the observed features may be divided into four somewhat overlapping stages of (1) differentiation and segregation, (2) intrusion, (3) consolidation, and (4) serpentinization. A summary of these events is presented in Table 3.

A magma of the composition necessary to produce the Moa ultramafic complex would be rich in magnesia and iron, deficient in silica, lime, and alumina, very low in the alkalies, and would contain a small amount of chromium and nickel. BOWEN [1928, pp. 145-172] believes that no liquid of this composition could exist in nature because of the high temperature which would be necessary to keep it molten, and cites the absence of any known effusive equivalents of these rocks as evidence against their crystallization from a magma of the same composition. Instead he postulates that they represent crystal accumulations of the early-forming ferro-magnesian minerals from a basaltic magma. The relative scarcity of gabbro associated with the Cuban peridotites has been used by HESS [1938 b, p. 323] as an argument against the possibility of the differentiation of a basaltic magma to produce the peridotite and associated rocks, and although more detailed mapping both in this area and especially in Camagüey has shown that feldspathic rocks are more common than Hess states, the writer agrees that the complex could not have resulted from the differentiation in place of a basaltic magma. If, however, differentiation occurred in depth, an ultramafic mass may have formed from a basaltic magma, and later, during intrusion, have been separated from the felsic fraction. Seismic records indicate the presence of a substratum with the density of peridotite at a depth of some 60 kilometers, and it is this layer which is believed to be the source of the material which forms the complex.

Segregation was probably accomplished through the crystallization and sinking of early-formed minerals which had a greater specific gravity than the surrounding liquid. The composition of the chromite, if it were the first mineral to form, should reflect the overall composition of the magma, since it belongs to an isomorphous group which includes spinel and magnetite as the other end members [STEVENS, 1944]. As alumina was in excess over chromic oxide, it seems improbable that a mineral of the composition of the Moa chromite could result from simple crystallization. BOWEN [1928, pp. 277-281], however, has proposed a process by which chromite could form from such a magma. Experiments with the system anorthite-forsterite-silica [ANDERSEN, 1915] show that the reaction of anorthite and forsterite with basaltic liquid at a temperature higher than 1320°C will produce spinel. Any chromic oxide present will enter the spinel molecule. Reversal of the reaction will again produce basic plagioclase and olivine, but chromic oxide, being unable to enter into these minerals, will remain behind, enriching the spinel in this constituent. Chromite will eventually be formed if the reaction is repeated often enough. It is suggested here that the accumulation of large masses of chromite deep within the peridotite layer may have been accomplished

Table 3--Summary of proposed mode of origin of the ultramafic complex

Stage	Processes	Results
Pre-differentiation	Homogeneous basaltic (?) magma	
Differentiation and segretation	Xlization of ol., an., and chrome-spinel	. . . .
	Sinking of xls, increase of Cr_2O_3 content thru reaction of spinel w. liquid to form ol. and an.	Xl. mush of ol., chromite, and liquid Chromite concentrated in one or more layers
Intrusion	Downbuckling of crust into "tectogene"	. . . .
	Intrusion of crystal mush into rocks of crust	Layered sill-like (?) complex of chromite masses in mush of ol. xls, w. interstitial pyroxenic and gabbroic liquid
	Start of crystallization of pyroxene	Formation of peridotite
	Laminar flow	Perfection of layering of perid., dunite and chromitite
	Fracturing of chromite masses	. . . .
	Injection of interstitial feldspathic liquid into joints in ore	Gabbro dikes in ore
	Reaction of chromite with pyroxenic liquid to form olivine	Dunite envelopes around ore
	Local turbulence in flow lines	Deviations of layering from normal attitude
Consolidation	Orientation of pyrox. by flow and stresses accompanying consolidation	Foliation of peridotite
	Shearing parallel foliation	Offset of pyroxene layers
	End of xlization of pyroxene	. . . .
	Inward stress from walls of intrusion chamber	Cross joints
	Injection of gabbroic liquid into joints	Gabbro dikes in peridotite
	Replacement of gb in ore by late solutions	Gabbro pegmatite
	Replacement of perid. by fdspthic solutions	Replacement "dikes" and zones in peridotite
Serpentinization	Continued stress	Longitudinal joints
	Reaction w. residual (?) water- and silica-rich solutions	Alteration of ol. and some pyrox. to serpentine
	Shrinkage (?), fissure filling by deposition from serpentine solutions	Chrysotile zones and veinlets

in the following manner. As spinel, formed either by reaction or direct crystallization near the top of the magma chamber, sank slowly downward, almost continuous reaction with the liquid surrounding it took place. Chromic oxide was taken into the spinel, while the excess of magnesia and alumina went into olivine and basic plagioclase. The spinel acted as a scavenger, gathering up most of the chromium in the magma before it reached the floor of the chamber or some other impediment to further sinking. Melting or diffusion in the solid state probably occurred to redistribute the constituents evenly throughout the mineral grains, as there is no evidence of zoning. Such zoning would be difficult if not impossible to detect, however, and may be present.

Olivine crystallizes in the same temperature range with spinel, and should also sink, although probably more slowly than the heavier spinel, which, it is assumed, was gaining in specific gravity as the content of chromium increased. The olivine would, however, remelt or be partially resorbed as it went down, thus allowing the chromite grains to pack relatively tightly even though they formed only a small proportion of the total volume of crystals. Anorthite did not sink alone, as its density was less than the average density of the liquid, but crystals attached to or enclosed in the heavier chromite and olivine would be carried down. The greater part of the basic feldspar associated with the ore probably is to be attributed to reaction between the rest magma and the spinel, rather than to the accumulation of entrapped anorthite grains. Pyroxene either was not crystallizing at this time, or was being converted to olivine as it sank into the subsilicic environment of the spinel. Most of the pyroxene is considered to have remained in the rest magma at this stage.

It is postulated that, by the process outlined above, an ultramafic zone with one or more chromite-rich layers was formed deep within the crust of the Earth. The chromite was more or less solid, while the silicates were in the state of a crystal mush sufficiently viscous to support the masses of ore.

HESS [1938 a], following Vening Meinesz, proposes that the great trough and strong negative gravity anomalies of the West Indies arc can be best explained by a deep buckle of the lighter upper crust of the Earth down through the basaltic substratum to the peridotite layer. He points out that the serpentines of Cuba probably indicate the former extension of this belt of anomalies, since during such a downwarping the peridotites would have ample opportunity for intrusion. The basaltic substratum, being plastic, is believed to have been pushed aside by the stronger rocks of the upper crust. Thus a mechanism is provided for the intrusion of the ultramafic product of a basaltic magma without the attendant accompaniment of the more felsic fraction.

HESS [1938 b, pp. 328-329] also suggests that a hydrous ultramafic magma is produced by the partial fusion of the peridotite substratum, and that it is this lowest melting fraction, essentially $H_4Mg_3Si_2O_9$ (serpentine), which is re-fused and expressed from the substratum to give rise to the intrusions of peridotite found in Cuba and elsewhere. The writer believes that a fatal weakness of this theory is that no chromite should be found anywhere in peridotite formed by this process, as chromite has the highest melting point of any of the constituents of ultramafic rock and would be left behind. It is proposed here instead that an entire section of the peridotite substratum was intruded into the lighter rocks of the crust as a mass of crystals with interstitial liquid. The liquid may have been derived by remelting, but the author thinks it more probable that it was the original rest magma which had never crystallized. If this rest magma contained the material from which the pyroxene and dikes later crystallized, it may have been as much as 15 to 25 per cent of the total. Some of the olivine may also have been fluid, although evidence such as that seen in the dunites of Kenai Peninsula, Alaska [GUILD, 1942, p. 144], for two generations of olivine is lacking. The proportion of crystals to liquid is believed to have been such that the mass had the requisite fluidity for intrusion and at the same time the necessary viscosity to carry upward with it blocks of the chromite layer or layers, which are believed to have consisted, at this stage, of loosely-packed crystals of chromite with interstitial silicate liquid. What this viscosity would be is not known.

During intrusion the layering, which may have been very rude in the substratum, was emphasized by the laminar nature of the flow. The larger chromite masses probably were not modified much from their original shapes, but small concentrations of individual grains may owe their perfection of layering to the effects of the moving mass. Similarly, the pyroxene-rich layers probably derive their regularity from the drawing out of less well-banded material. Toward the end of the period of intrusion local turbulence produced the swirls such as the bend in the pyroxene layers seen in Figure 14 and the prominent roll in the Cayoguán ore body. The ability of a thick ore mass to bend at this late stage is believed to have been due to a relatively high proportion of interstitial silicate liquid, much of it feldspathic, which is to be expected from the postulated manner of accumulation of the ore mineral. This interstitial liquid was a close and ready source for the dike material. As the ore began to fracture under the stresses imposed upon it during intrusion, a filter pressing or lateral secretion of the liquid into the open joints took place. The resultant packing of the chromite grains produced the close-textured ore seen today. The great preponderance of dikes in ore over those in peridotite therefore has a logical explanation, as does the lack of any evidence of feeders for these dikes.

During intrusion the temperature was still sufficiently high that the reaction between spinel and pyroxene to form olivine and plagioclase was possible, and it is to this reaction that the dunite envelopes around the deposits are attributed. SHAND [1945, p. 250] points out that reactions in essentially solid rocks take place between wandering ions in an open system where there can be no exact balancing of equations; here one phase, the chromite, was solid, while the other may, for all practical purposes, be considered as liquid, as the pyroxene probably was converted to olivine as it crystallized. Equation (1), from which iron has been omitted, expresses in simple form the reaction believed to have occurred:

$$\underset{\text{(enstatite)}}{MgSiO_3} + \underset{\text{(spinel)}}{MgAl_2O_4} \rightarrow \underset{\text{(olivine)}}{Mg_2SiO_4} + \underset{\text{(corundum)}}{Al_2O_3} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Corundum is not known from these rocks; the excess alumina would perhaps stay behind in the chromite molecule, of which the spinel is only a fraction. Enstatite, however, forms only part of the pyroxene crystal. Diopside is present in all the orthopyroxene, constituting nearly ten per cent of the mineral, and as HESS and PHILLIPS [1938] show, the CaO content is quite uniform at about 2-1/4 per cent in many orthopyroxenes. It is suggested that the following chemical statement gives a better picture of what took place:

$$\underset{\text{chromite}}{(Mg, Fe)O\cdot(Cr_2O_3, Al_2O_3, Fe_2O_3)} + \underset{\text{enstatite}}{(Mg, Fe)O\cdot SiO_2} + \underset{\text{diopside}}{CaO(Mg, Fe)O\cdot 2SiO_2} \rightarrow$$

$$\underset{\text{olivine}}{2(Mg, Fe)O\cdot SiO_2} + \underset{\text{anorthite}}{CaO\cdot Al_2O_3\cdot 2SiO_2} + \underset{\text{chromite}}{(Mg, Fe)O\cdot(Cr_2O_3, Fe_2O_3)} \ldots\ldots\ldots \quad (2)$$

Part of the alumina would be taken up in the basic plagioclase, and the proportions of the constituents of the chromite would be changed somewhat. A rough estimate of the amount of feldspar formed by this reaction may be made as follows: The average pyroxene content of the peridotite is 25 per cent. The lime content is 2-1/4 per cent of the pyroxene, or slightly more than half of one per cent of the total. As anorthite is roughly 20 per cent CaO, a volume equal to 2-1/2 per cent of the dunite envelopes might be converted to feldspar. At least this amount is found in the dikes and replacement masses near the ore bodies. The presence of larger quantities of feldspar in some places and its complete absence in others suggests that it also was mobile and capable of concentration, like the feldspar within the ore.

The bulk of the pyroxene crystallized during the closing stage of intrusion, just before final consolidation. Slight shearing stresses, set up parallel to the average attitude of the layering by the continuing pressure of the magmatic flow, tended to orient the pyroxene grains, thus developing the foliation of the peridotite. The offset of the pyroxene layer (see Fig. 18) dates from this stage, when there was still sufficient melt to heal the fracture.

As long as an appreciable part of the complex was fluid, the walls of the intrusion chamber were held apart by essentially non-directional hydrostatic pressure. Upon crystallization of this liquid fraction, however, an important change occurred in the nature of the stresses being applied on the mass. The dominant pressure was now one directed inward from the walls more or less at right angles to the lines of flow which had controlled the orientation of the planar structures, and the direction of easiest relief (or major axis of the strain ellipsoid) was parallel to the flow. The cross joints developed along conjugate shear planes, making small angles to the direction of greatest stress, one plane usually predominating over the other, and a slight tension opened up a few of these joints to receive injections of gabbro from small local reservoirs of rest magma which had not yet crystallized.

Very little is known about the overall shape of the intrusion, but some speculations may be in order at this point. Although it is of batholithic proportions, the structural relations of the complex are suggestive of a large sill from which the upper cover has been removed. If the mass was intruded into the flank of a downbuckle as Hess proposes, it seems possible that it might be sill-like in shape in spite of its size. The known ore deposits may be restricted to the Franklyn-Potosi zone because the central part of the sill, being the last to consolidate, was drawn from the deepest portion of the substratum, and the arching of the roof might account for the prominent swing in the structure lines in the Cayoguán group. The data on hand are insufficient to answer these questions, but additional field mapping might lead to more conclusive results.

Relatively dilute solutions, the product of the end stage of crystallization of the normal minerals, were present in small quantities at the close of the period of consolidation. They rearranged the constituents of the normal-textured rock in some dikes to form the coarse pegmatites but did not alter their bulk composition appreciably. As the fractured chromite was more permeable than the peridotite, which was still semiplastic, these solutions had better access to the dikes in ore than to those in the country rock. The restriction of the pegmatite to dikes in ore may be due also to a relative inertness of the chromite to the solutions at the temperature now prevailing, as contrasted with the still chemically active wall rock of the dikes in peridotite. In the former the solutions could react only with the gabbro, whereas in the latter their effectiveness was dissipated by the entire mass. Where they were restricted to relatively narrow channels in peridotites they formed replacement "dikes" and irregular replacement bodies.

The evidence in this district is in accord with the theory developed by BENSON [1918], HESS [1933], and others that serpentine is a product of the same igneous cycle which produced the peridotite and associated rocks; in other words, that it is caused by the autometamorphism of the original silicates by residual solutions present in the complex itself or picked up shortly after intrusion. The constant association of the chrysotile zones and veinlets with the longitudinal joints, themselves clearly related genetically to the forces which accompanied the intrusion, indicates that serpentinization closely followed consolidation. The relation of these joints to the stresses which produced the cross joint set is not understood, but the deformation of pyroxene grains (see Fig. 23) shows that they are the result of shearing couples. The intense serpentinization along the sheeted zones is due in part to the opportunity for circulation of solutions along the fractures, and in part to the fact that serpentine, and particularly chrysotile, appears to be a stress mineral. In pyroxene-rich layers, where it is protected from stress by the large enstatite grains, olivine is quite fresh; in contrast the dunite layers are considerably altered. Although it is difficult to distinguish the relative importance of fractures and permeability versus stress in this alteration, the intersecting lines of strain in the chrysotile veinlets show that stresses were active during their formation. It seems probable that stress played a role in the orientation of the fibers.

HESS [1933, pp. 651-653] believes the process of serpentinization can best be represented by the equation:

$$3Mg_2SiO_4 + SiO_2 + 4H_2O \rightarrow 2H_4Mg_3Si_2O_9 \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This reaction involves a loss of specific volume of approximately five per cent, instead of the expansion required for other equations, and seems to accord with the facts in so far as they are known. The apparent expansion implied in the fissure filling of the innumerable parallel joints, best seen in Figure 15, is then caused simply by the simultaneous overall shrinking of the rock and filling of the resultant fissures. If the rock is 50 per cent altered, the shrinkage would be 2-1/2 per cent. The chrysotile veinlets may represent part or all of the decrease, as a 1/10-inch veinlet every four inches would compensate for this.

One of the unsolved problems of serpentinization is the source of the water necessary to effect the alteration. Some simple calculations show that about six per cent of the weight of the peridotite is water, as approximately one-half of it is now serpentine, a mineral which contains 12.9 per cent H_2O. If all this water was contained in the 25 per cent or less of rest magma interstitial to the olivine and chromite at the time of intrusion, the liquid would have about 25 per cent of moisture, which would increase steadily as pyroxene crystallized until the stage of serpentinization began. Improbable as this appears, the alternative source is the intruded country rocks, which, being schists, metavolcanics, and diorites, could not be expected to contain much water. Even though the water were available in them, no mechanism is known to the author for absorbing and distributing it evenly throughout the consolidating ultramafic complex. It appears likely, therefore, that the water was of magmatic origin.

Relation to broader problems of ultramafic rocks

The structural relations and petrography of the Moa district indicate that these chromite deposits are of early magmatic, probably pre-intrusion origin. The evidence substantiates Bowen's views on the formation of ultramafic rocks by the gravity segregation of early-formed minerals and the subsequent intrusion of these rocks as inhomogeneous aggregates of crystals and interstital liquid. It is suggested that much of the controversy over the origin of chromite has arisen through the confusion of secondary features for primary ones which have been obscured or obliterated either by intense deformation and thorough serpentinization at the time of intrusion or by later orogenies. The ultramafic rocks are commonly found in highly-deformed belts, presumably because it is in such belts that the crust has been depressed into the peridotite substratum. The Moa complex may, therefore, be a relatively rare example of an injected peridotite in which primary structures are preserved. The term "injected" is used to distinguish this type of intrusion from that of the Bushveld [DALY, 1928; HALL, 1929] and Stillwater [PEOPLES, 1936] complexes in which magmas of noritic composition have been differentiated by gravity segregation after intrusion into the part of the crust in which they are now found. In contrast the Moa complex, according to the hypothesis proposed here, may be considered as having originated in much the same way, but prior to at least the last stage of intrusion, so that only the fragments of the chromitite layer preserve the original stratification. This oversimplification ignores many factors, such as the composition of the magmas, which have been shown to be quite different from the evidence of the chromites themselves [THAYER, 1946], and the relations of the ore to the enclosing silicates, which SAMPSON [1932] has interpreted as indicating a late magmatic age for the chromite, but it is believed to explain the principal reason for the occurrence of two distinct types of chromite deposits, the stratiform and the sackform. The former type is probably best exemplified in the Bushveld and Stillwater complexes, where thin chromitite layers can be traced for miles; the latter is the common type in the unlayered peridotites, where comparatively equidimensional deposits are scattered apparently at random through the enclosing rock. It is proposed that the two types originated in essentially the same manner and owe their present differences not to their mode of formation but to their later histories.

The differentiation of the magma and formation of the ore deposits at great depth afford ample opportunity for the development of features which can best be explained by the presence of actual liquids of an extreme type. The objections to them based on the temperatures involved are not so difficult to overcome in this environment as in one high in the crust. Veinlets of chromite in silicate minerals, reported by FISHER [1929], SAMPSON [1931], and others (but not seen in the Moa district), and of dunite dikes in chromite and peridotite may result from the remelting of small quantities of crystals.

A lack of metamorphism of the country rocks by the intrusion of peridotite, a feature which has puzzled many investigators, may be attributed to two factors: (1) The intrusion does not occur until after chromite and olivine have crystallized, and the temperature is therefore well below that necessary to keep them molten. The Moa complex was intruded at about the time pyroxene was forming. These pyroxenes are believed by HESS and PHILLIPS [1938, pp. 454-455], from the evidence of the exsolution lamellae of diopside, to have crystallized below 1130°C, and the substantial proportion of water present may have reduced this temperature considerably. (2) The entire moisture content of the complex is used up in the process of serpentinization, and additional water may pass inward toward, rather than outward from, the intruding rock. Thus even though the proportion of water is unusually high, none is available for the metamorphism of the surrounding rocks. As these rocks are themselves already at a fairly high temperature, owing to their downwarping into the "tectogene," the moderate heat of the peridotite does not affect them further. It seems probable, therefore, that less contact metamorphism is to be expected from the intrusion of a peridotite than of a more acid rock, which in the crystallization of anhydrous minerals expels its moisture content into the surrounding rock.

Conclusion

The preservation of primary structures in the rocks of the Moa ultramafic complex has made possible the application of both detailed structural field mapping and petrofabric analysis to the problems of the origin of the silicate rocks and chromite deposits of the district. The results indicate that differentiation of a basaltic (?) magma produced a mafic fraction of crystals of olivine and chromite, with interstitial liquid, which was intruded into the lighter rocks of the crust during a period of severe downbuckling. Similar conclusions were reached for the origin of the Camaguey ultramafic complex [FLINT, DE ALBEAR, and GUILD, in press] because of the areal distribution of the feldspathic rocks and chromite deposits of that district. It is suggested that detailed work may show that these methods can be applied to other areas of peridotite and allied rocks, and that the mode of formation proposed here is a common one for ultramafic rocks.

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A FLOOD-ROUTING DEVICE

I. H. Steinberg

In recent years the problem of flood routing has received a great share of attention. In design of flood-control works or river and harbor improvements the engineer is often called upon to determine the effects of natural valley storage, reservoirs, and navigation projects on flood flows and stages. Many methods and procedures have been developed for the purpose of facilitating and simplifying the calculations for the flood-routing problems. Elaborate flood-routing machines and linear and circular slide rules have been devised. However, the flood-routing machines have not proven popular owing to their high cost of construction. The slide rule has the disadvantage that a different set of scales is required for each relation between discharge and storage, and it is not readily adaptable to change of time interval.

Several years ago STEINBERG [1938] developed a method of flood routing utilizing a sloping line for solving for the values of the discharges. As an outgrowth of this method, a fairly simple and inexpensive device was developed by which the discharges could be solved semi-graphically with the minimum of computations. Other advantages of the device are that it can be used with any curve, or family of curves, of relation between discharge and storage, it permits change in time interval, and it is easily adapted to routing where the storage is a simple function of the weighted inflow and outflow [McCARTHY, 1938].

The routing device consists of two slides to which are attached arms with adjustable slopes. One of the slides has a linear scale graduated in inches and tenths of an inch. The details of the flood-routing device are shown by Figure 1. The dimensions of the device have been adapted for use with a sheet of graph paper 11 by 17 inches.

Theory--The basic equation for flood routing is

$$[(I_1 + I_2)/2]t + S_1 = [(Q_1 + Q_2)/2]t + S_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

which may also be written in the form

$$i_{(1-2)}t + S_1 = [(Q_1 + Q_2)/2]t + S_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where I_1 and I_2 are the inflows in cfs at the beginning and end of the period, (1 - 2), respectively, $i_{(1-2)}$ is the average flow during the period $(1 - 2) = [(I_1 + I_2)/2]$, Q_1 and Q_2 are the outflows in cfs at the beginning and end of the period, (1 - 2), respectively, S_1 and S_2 are the storages in cfs-days at the beginning and end of the period, (1 - 2), respectively, and t is the time interval, in days.

Equation (2) can be written as:

$$i_{(1-2)}t - Q_1t/2 + S_1 = Q_2t/2 + S_2 = M_{(1-2)} \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $M_{(1-2)}$ is the storage factor for the period (1 - 2).

If $M_{(0-1)}$ is the storage factor for the preceding period, then,

$$M_{(1-2)} = M_{(0-1)} - Q_1t + i_{(1-2)}t = Q_2t/2 + S_2 \quad \ldots\ldots\ldots\ldots \quad (4)$$

If the storage is a simple function of the weighted inflow and outflow of the form:

$$D = IX + (1 - X)Q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

from which

$$Q = D/(1 - X) - IX/(1 - X) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

Equation (4) becomes:

$$M_{(1-2)} = M_{(0-1)} - D_1t/(1 - X) + i_{(1-2)}t/(1 - X) = D_2t/2(1 - X) + S_2 \quad \ldots\ldots \quad (7)$$

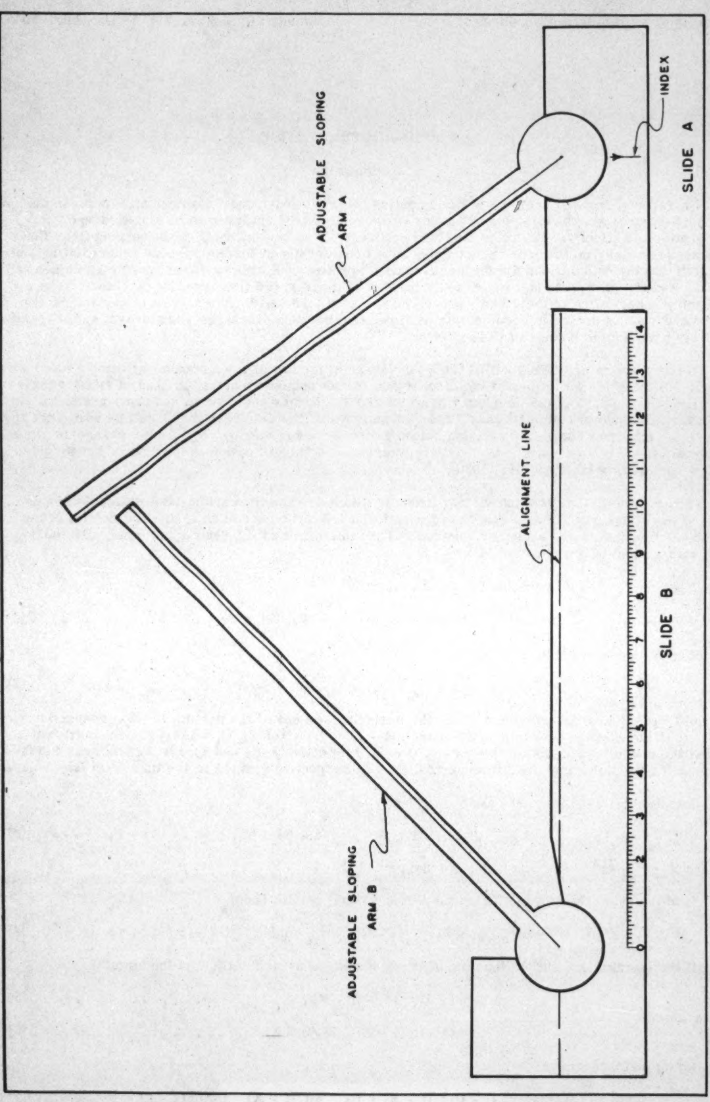
ADJUSTABLE SLOPING ARM A
INDEX
SLIDE A
ALIGNMENT LINE
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
SLIDE B
ADJUSTABLE SLOPING ARM B

Fig. 1--Details of the flood-routing device

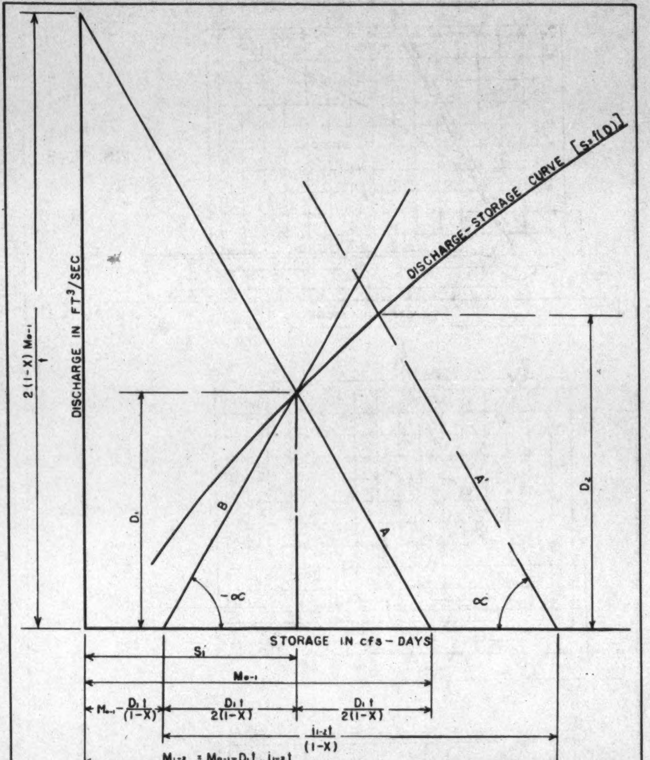
2(1-X) M₀₋₁
DISCHARGE IN FT³/SEC
DISCHARGE-STORAGE CURVE [S=f(D)]
D₁
D₂
B
A
A'
-∝
∝
STORAGE IN cfs-DAYS
S₁
M₀₋₁
M₀₋₁ - D₁t/(1-X)
D₁t/2(1-X)
D₁t/2(1-X)
i₁₋₂t/(1-X)
M₁₋₂ = M₀₋₁ - D₁t/(1-X) + i₁₋₂t/(1-X)

Fig. 2--Illustration for computing by means of the flood-routing device

The value of X depends upon the characteristics of the reach of the stream under consideration and varies from zero to 0.5.

In the usual problem of flood routing the values of $i_{(1-2)}$, Q_1 and S_1 are known, with the value of Q_2 to be obtained. Often the final storage, S_2, may also be desired.

The equation $M_{(1-2)} = D_2t/2(1-X) + S_2$ is an equation of a straight line in D and S for any given value of M, since t and X are constants.

For $D_2 = 0$, $S_2 = M_{(1-2)}$, and for $S_2 = 0$, $D_2 = [2(1-X)M_{(1-2)}]/t$.

The intersection of the straight line, as defined above, for any given value of M with the curve of relation between discharge and storage defines the values of D_2 and S_2.

In Figure 2 let line A represent the graph of equation $M_{(0-1)} = D_1t/2(1-X) + S_1$ for the period $t_{(0-1)}$.

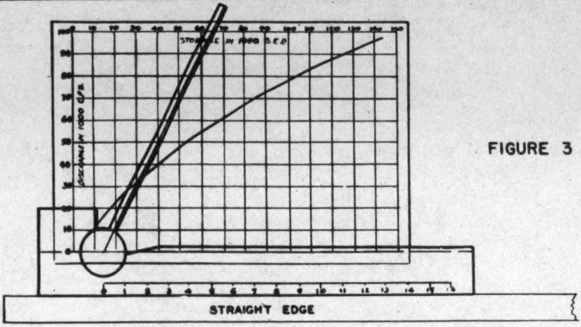
STORAGE IN 1000 S.F.D
DISCHARGE IN 1000 c/s
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
STRAIGHT EDGE

FIGURE 3

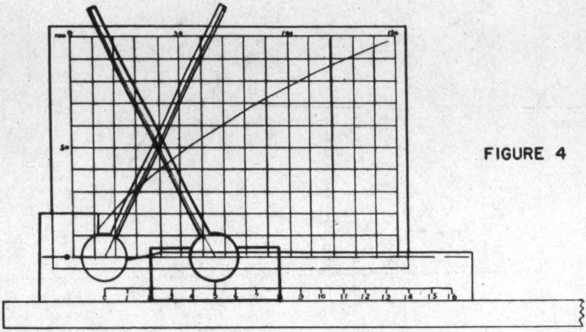
100
50
100
150
50
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

FIGURE 4

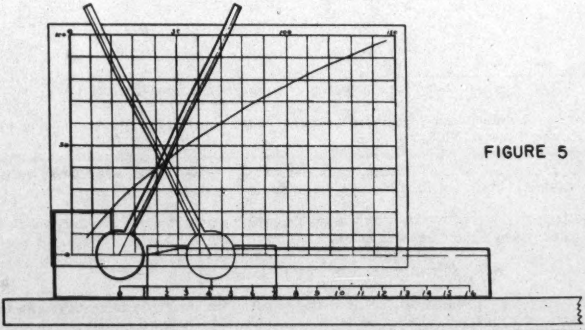
100
50
100
150
50
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

FIGURE 5

Examples of use of the flood-routing device for a time interval, t, equal to one

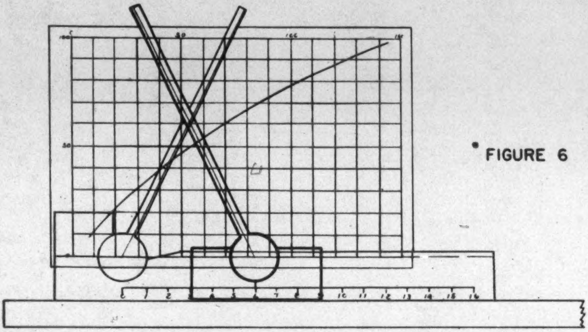
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FIGURE 6

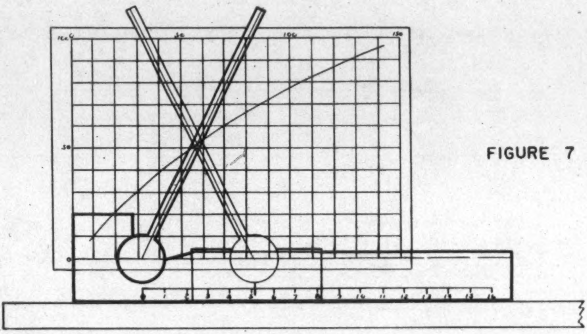
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FIGURE 7

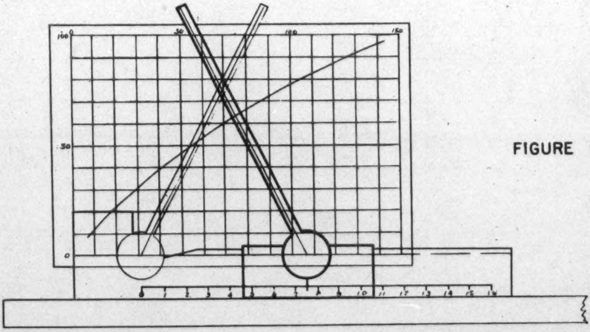
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FIGURE 8

Examples of use of the flood-routing device for a time interval, t, equal to one

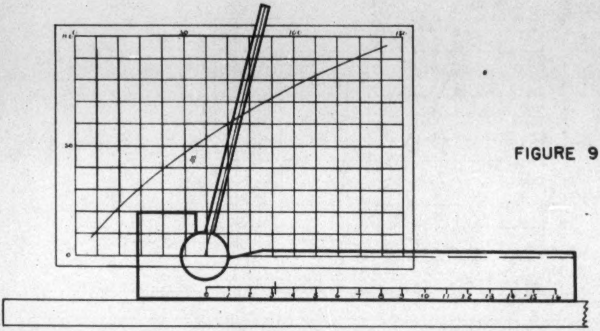
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FIGURE 9

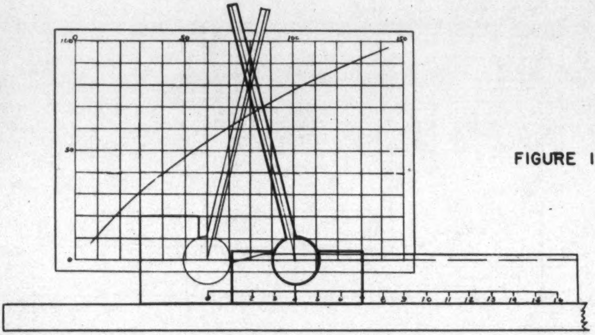
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FIGURE 10

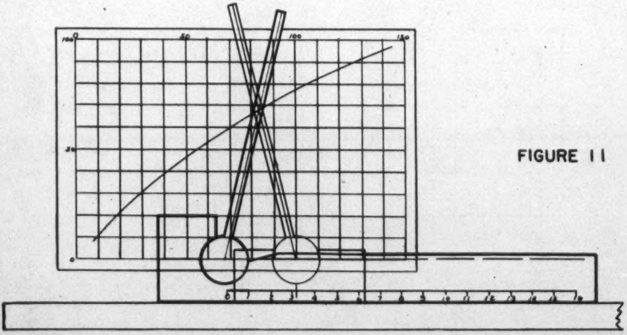
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FIGURE 11

Examples of use of the flood-routing device for a time interval, t, equal to one-half

If a straight line is drawn through point D_1 (the intersection of line A with the storage curve) with a slope the negative of that of line A, the line will intersect the S axis at a point $M_{(0-1)} - D_1t/(1 - X)$.

If the value of $i_{(1-2)}t/(1 - X)$ is then laid off along the S axis from this point of intersection, the value of $M_{(1-2)}$ will then be found graphically. Drawing line A′ through the point $M_{(1-2)}$ on the S axis, and parallel to line A will give the value of D_2 (and S_2 if desired) on the discharge-storage curve.

To find the value of M for successive time intervals it is necessary only to lay off the value of $it/(1 - X)$ along the S axis from the point of intersection of line B with the S axis as defined by the value of D_1 at the beginning of the period. This is readily accomplished by means of the flood-routing device, which gives a direct solution for the values of D (and S) without the necessity of first computing the values of M. The values of Q are then determined from equation (6).

Application--The use of the flood-routing device is illustrated by the accompanying examples and by Figures 3 to 11. Since one inch on the scale of Slide B will represent 10,000 cfs-days on the storage scale, the values of it in the example are first divided by 10,000, which is called the scale constant, c. If the storage had been plotted to a scale of one inch equals 5000 cfs-days, then c would be equal to 5000.

The discharge-storage curve is first fastened firmly to the desk or table, by means of Scotch tape. Slide B is then placed so that the alignment line coincides with the S axis, and is held in alignment by means of a straight edge. The slope for arm A is determined from the equation $M = Dt/2(1 - X) + S$.

The slope for arm B is the negative of A. Slide A is then placed over Slide B and the device is ready for use in routing. In the examples the average inflows, i, are known as is also the value of the outflow at the beginning of the initial period. In Example 1, the value of X has been assumed as zero, and the storage is thus a function of the outflow. In Example 2, a value of $X = 0.2$ has been assumed.

Example 1

(a) Set up Slides B and A as explained above, with the slopes set for $t = 1$ and $X = 0$. The slope for arm A can be readily determined by laying off one unit on the storage scale and two units on the discharge scale (from equation $M = D/2 + S$). The slope for arm B is the negative of A.

(b) Move Slide B so that the hair line on arm B intersects the value of 31,000 cfs, the initial value of outflow (see Fig. 3).

(c) Move Slide A until index line intersects the value of 5.0 (see Fig. 4).

(d) Read, Q = 42,000 cfs on storage curve at intersection of arm A with curve. (Note: The value of the storage may also be recorded at the same time if desired.)

(e) Move arm B to intersection of arm A with storage curve (to value of Q = 42,000 cfs)(see Fig. 5).

(f) Move index of Slide A to value of 6.0 (see Fig. 6).

(g) Read, Q = 52,000 cfs.

(h) Move arm B to this value (see Fig. 7).

(i) Move index of Slide A to value of 7.5 (see Fig. 8).

(j) Read, Q = 63,500 cfs.

(k) Adjust slopes of arms for $t = 1/2$ day. (For $t = 1/2$, the slope is obtained by laying off four units on the discharge scale and one unit on the storage scale.)

(l) Move arm B to value of 63,500 cfs on the storage scale (see Fig. 9).

(m) Move index of arm A to value of 4.0 (see Fig. 10).

(n) Read, Q = 68,000 cfs.

This process is repeated for the remaining period to give the values of Q as indicated in the tabulation.

Table 1--Tabular presentation of data found in Example 1

Date	t	Average inflow i	it/c	Outflow	
				Instantaneous[a]	Average
	days	cfs	cfs-days	cfs	cfs
				31,000[a]	
April 26	1	50,000	5.0	42,000	36,500
27	1	60,000	6.0	52,000	47,000
28	1	75,000	7.5	63,500	57,800
29	1/2	80,000	4.0	68,000	65,800
29	1/2	85,000	4.25	72,200	70,100
30	1/2	80,000	4.0	74,100	73,200
30	1/2	75,000	3.75	74,400	74,200

[a] Initial value of instantaneous outflow is given as 31,000. All other figures in this column are computed.

Example 2

The process is similar to that of Example 1 except that the slopes of the arms are defined by the equation $M = Dt/2(1 - 0.2) + S = Dt/1.6 + S$.

For the purpose of illustration the same values of inflow and initial outflow as in Example 1 have been used.

Table 2--Tabular presentation of data found in Example 2

Date	t	Average inflow i	it/0.8c	Weighted discharge		0.2i	D - 0.2i	Average[a] outflow
				Instantaneous	Average			
	days	cfs	cfs-days	cfs	cfs			cfs
				31,000				
April 26	1	50,000	6.25	43,800	37,400	10,000	27,400	34,200
27	1	60,000	7.50	53,200	48,500	12,000	36,500	45,600
28	1	75,000	9.38	65,900	59,600	15,000	44,600	55,900
29	1/2	80,000	5.00	70,600	68,200	16,000	52,200	65,200
29	1/2	85,000	5.31	75,500	73,000	17,000	56,000	70,000
30	1/2	80,000	5.00	77,200	76,400	16,000	60,400	75,500
30	1/2	75,000	4.69	77,100	77,200	15,000	62,200	77,900

[a] Equals (D - 0.2i)/0.8

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U. S. Engineer Office,
St. Paul, Minnesota

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MACROTURBULENCE IN NATURAL STREAM FLOW

Gerard H. Matthes

Abstract--Six types of macroturbulence phenomena in natural streams are discussed: Velocity and stage surges which are rhythmic or cyclic; eddying which is continuous; upward and downward vortex actions which are intermittent; transverse oscillations of water surface and helicoidal effects, which are continuous. These are all caused by channel roughness but do not appear to be related to microturbulence. However, the eddy and vortex types, which are flow separations, dissipate through disintegration at their peripheries into macroturbulence. A new term, "kolk," is introduced to supplement a deficiency for designating upward vortex action, considered one of the most prolific as well as important forms of stream dynamics. The need for additional research is emphasized.

Introduction--This paper is presented in an endeavor to stimulate research into the large-scale turbulence phenomena peculiar to the dynamics of natural stream flow. The term macroturbulence, as here used, has been found an appropriate as well as convenient connotation for these phenomena, differentiating them as it does from the small-scale or microturbulence phenomena to which much research in fluid mechanics has been devoted.

The classification of macroturbulence phenomena herein submitted is based largely on observations made by the writer over a period of 15 years on natural channels ranging from brooks to rivers the size of the Lower Mississippi. Correlation was thus made possible between small clear-water streams and large turbid rivers, the limitations for making observations encountered in the first being compensated by readily observable action in the latter, and vice versa. Thus, the Lower Mississippi, because of the magnitude and abundance of its macroturbulence, revealed features which become dwarfed to insignificant proportions in shallow streams or in laboratory models. On the other hand, small clear-water streams having clean, white, sandy bottoms and transporting in their bed loads brown gravel, were found to offer exceptional advantages for close-up underwater observations which were impracticable in the Mississippi. In addition, the writer's studies have included detailed examinations of dry river beds in the arid western states, particularly in canyons exhibiting bare ledge-rock bottoms, and boulder-strewn beds. Occasionally, a stream like the Feather River in California offered the unusual opportunity for studying highly turbulent flow and for correlating its turbulence phenomena with its bed-erosion features seen in the dry during periods when all water was diverted for power-generation purposes.

Classification--The more important dynamic processes studied are listed in Table 1.

Terminology--Sparing use has been made of the word "eddy," a term which has become promiscuously applied to different stream-dynamics phenomena. In this paper "eddy" denotes any rotating fluid motion which possesses continuity so long as the flow pattern which creates it continues to prevail. Bottom rollers of forms II(3) and (4) operate also in this manner and are here classed as eddies. "Roller," as applied to eddies, is common usage but tends to convey a cylindrical shape which is not always realized in ordinary stream channels, where the axes of eddies, especially of those close to a bank or bottom, tend to be curving rather than straight.

Bed deepening by vortex action induced by upward displacement of a body of water is one of the commonest as well as most important forms of macroturbulence in natural streams, but has earned as yet no proper designation in the English language. Its dissipation at the surface in the form of a so-called "boil" has been responsible for its being confused with similar surface disturbances such as those caused by the movements of boats. As "boil" utterly fails to be descriptive of the subsurface vortex action, the writer has searched foreign literature for a suitable word and found "kolk," applied by Dutch engineers to this vortex-type of bed deepening. a convenient and also descriptive term. CRUGNOLA [See "References" at end of paper, 1902] used "kolk" to designate the deepest part of the talweg. Professor REHBOCK [1925 a] used it in his discussion of the dentated sill, but applied it loosely to bed scour in general. The writer recommends the adoption of "kolk" by American engineers, restricting its use, however, to the original Dutch meaning, which denotes bed deepening by vortex suction. The word is so used in this paper.

Table 1--Classification of macroturbulence phenomena in natural stream flow

Type of motion	Form of macroturbulence	Characteristics
I Rhythmic and cyclic surges	(1) Velocity pulsations	Inherent in all natural stream flow, affect bottom velocities more than surface velocities
	(2) Water-surface fluctuations	Periodic rise and fall of water surface is shown on graphs of recording gages but is observable also on staff gages, strongest during high rising stages, decreasing in intensity during falling stages
	(3) Surge phenomena of considerable magnitude produced by abnormal channel conditions	Local, occur at abrupt changes in direction of flow, manifested by a cycle of alternate elevation and subsidence of water surface with clocklike regularity, accompanied by eddying currents which reverse their direction of flow in some cases as a definite feature of the cycle
II Rotary, continuous	(1) Slow bank eddies or rollers	Have quasi-vertical axes, occur in bays or pockets where channel has excessive width, collect floating drift, promote deposition of materials in suspension and are a cause of shoaling
	(2) Fast bank eddies or rollers, sometimes called suction eddies	Have quasi-vertical axes, cause active bank erosion, occur at upstream as well as downstream ends of bridge abutments, bank protection works, and projecting ledge rock; erosive action often extends downward causing local bed deepening; small eddies of this general type occur at bridge piers and piling in the channel
	(3) Slow bottom rollers	Have quasi-horizontal axes, occur during low-water stages where channel bottom has excessive depth, promote sedimentation, cease during flood stages when renewed bed deepening takes place
	(4) Fast bottom rollers	Have quasi-horizontal axes, occur during high stages downstream from artificial or natural bed sills or low obstructions, cause bed deepening extending to considerable depths, which progresses upstream toward the sill or obstruction with tendency to undermine it
III Vortex action, upward, intermittent rather than periodic	(1) Short-lived, local, upward displacements of water entraining bottom materials, terminate at surface in nonrotating boils	Action is upward with strong and swift vortex motion at stream bed where suction lifts materials, during ascent rotary motion loses intensity and heavier materials drop out, energy of propagation suffices to raise bulk of displaced water and much of finer materials entrained to surface, boil protrudes above latter to variable heights and does not rotate, occurs along axis of main current and at any other points where sufficient energy develops, primary agency responsible for rapid bed deepening during rising stages weak during low stages
	(2) Vertical-axis vortices at submerged obstructions such as tall boulders, operate on upstream and downstream sides, ending in nonrotating boils at surface	Action is upward with strong and swift vortex motion at stream bed where it develops powerful suction, rotary motion loses intensity during ascent, no trace of it appearing at the surface, but energy of propagation is sufficient to carry water and bed materials so raised over the obstruction in the shape of a boil, short-lived, repeated

Table 1--Classification of macroturbulence phenomena in natural stream flow (concluded)

Type of motion	Form of macroturbulence	Characteristics
III (concluded)	(2) (concluded)	at brief intervals, primary agency responsible for pothole formation in rock beds and along canyon walls
IV Vortex action, downward, sustained but subject to interruptions	(1) Vortex axes inclined in direction of flow, trending downwards, cause erosion by fluting on submerged stationary boulders and projecting rock masses in river bed and along canyon walls	Small vortices which chisel down the corners and edges of submerged stationary rock masses during intense velocities of flood flow, produce fluting commonly seen in canyons and mountain streams, action is sustained but subject to interruptions caused by temporary changes in current direction
V Transverse oscillations	(1) Superelevation of water surface at concave banks of bends	Produces slope of water surface at right angles to axis of flow except at crossings where surface normally is level across the channel
VI Helicoidal, continuous	(1) Helicoidal flow at bends	Peculiar to deep and narrow channels, in wide and shallow streams takes on an abortive form
	(2) Double helicoidal flow in straight channels	Occurs only in long straight reaches having deep rectangular or trapezoidal cross sections, not observable in wide and shallow streams

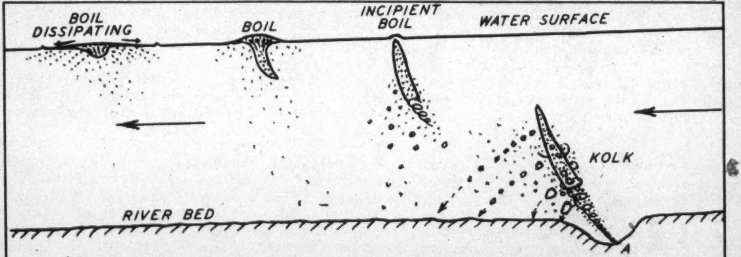
Fluid-mechanics aspects--In this discussion all extraneous influences on stream flow are eliminated from consideration. By extraneous influences are meant changes in force or direction of winds, sudden heavy rainfall, the return into the channel of overbank flow during flood subsidence, and cloud-burst runoff contributed locally by some tributary. So viewed, the rhythmic forms of Type I appear to be manifestations of the constant readjustments of the equilibrium of flow which take place in all forms of flowing water. In natural streams this unsteadiness is augmented by ceaseless fluctuations in water discharge and in sediment load, as well as by momentary changes in channel capacity in any cross-section due to arrival or departure of bedload. The unstable flow conditions so created reach maximum proportions shortly prior to the arrival of a flood crest and continue until a short time after the crest has passed. In a river the size of the Mississippi such discharge and gage-height fluctuations are nothing short of extraordinary and account for the vexatious apparent inconsistencies experienced in discharge measurements made at such times. In the smaller streams similar instabilities occur on a lesser scale.

Velocity pulsations of form (1) are irregular as regards magnitude and frequency, and appear to be affected by the vacillating movement of the bedload. The clocklike regularity of the water-surface fluctuations of form (2) are stage-transmission effects, whose periodicity persists with remarkable uniformity throughout high and low stages, but whose amplitude increases with rising and decreases with falling stages. Their recurrence interval appears to be a function of average pool length, judging from tentative applications of the celerity formula for wave travel. Over a stretch of several hundred miles of the Lower Mississippi, in which the pool lengths before artificial cutoffs were made, averaged about five miles, the cycle of surface fluctuations averaged from 18 to 20 minutes, and the amplitude ranged from less than 0.05 foot during low stages to as much as 0.4 foot at the crest of the great flood of February 1937.

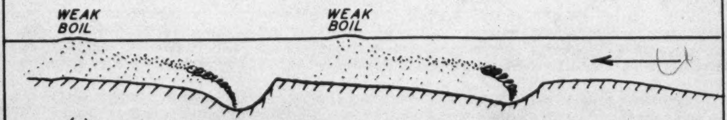
Surge phenomena of form (3) appear to be related to the water-surface fluctuations previously discussed, their respective frequencies of recurrence being nearly the same. Reversal of eddy currents set up by them is a common characteristic. These are found in rivers of such widely different types as the Lower Mississippi and the International Rapids Section of the St. Lawrence.

Eddies or rollers of Type II possess continuity of motion. Once a certain pattern of flow sets up an eddy at an obstruction, the eddying motion continues unbroken until the pattern ceases. Eddies constitute flow separations which are not related to the microturbulence whirls which pervade the main body of stream flow. However, at the peripheries of macroturbulence eddies disintegration takes place in the shape of minor eddies having counter rotation [BAKHMETEFF, 1945], with final dissipation of these minor eddies into still smaller ones and finally into microturbulence. Most flow separations caused by inequalities in the faces of banks, or at structures such as piles, bridge piers, and abutments [BAKHMETEFF, 1943] belong in the class of Type II eddies. Bottom rollers function in the same manner except that their axes are horizontal or nearly so. Observations on eddies, in the laboratory and in nature, as made by REHBOCK [1925 b] and others [JAKUSCHOFF, 1932, and SALOMON, 1926] have by no means exhausted the potentialities of this phenomenon from the point of view of fluid-mechanics research. Judging from surface observations the microturbulence bodies rising to the surface of the Mississippi River do not appear to be affected by nearby macroturbulence.

In marked contrast with the continuity of Type II eddying is the spasmodic Type III upward displacement of large volumes of water which induce vortex suction capable of lifting not only bedload materials but of gouging scour holes and potholes into resistant beds. The action is short-lived but frequent, typical of other hydraulic cavitation and lesser suction phenomena. The velocity of rotation at the pointed end of the vortex is of a high order, many times greater than the velocity of the surrounding stream flow. In shallow waters, small kolks are readily studied [see Fig. 1 (b)]. They develop weak suction which raises only sand grains and scatters these in the flowing body of the stream; the resulting boil also is weak [LANE, 1944]. In deep, swift waters [see Fig. 1 (a)], during rising flood stages, the kolk assumes large proportions, develops cavitation, and becomes an important agency in bed-scour and pothole formation. Its lifting force raises bed materials toward the surface with great velocity, entraining gravel and cobblestones from coarse bed loads. The action in clear water and in sediment-laden water is essentially similar. As a fluid-mechanics phenomenon it is in many respects similar to tornadic action, taking into account the differences in viscosity of water and air. As in the tornado, the whirling vortex action of the kolk loses force in the ascent, and much of the entrained material drops out as the upward forces diminish in intensity. Kolks dissipate at the surface in the form of boils in which the water pushed up to the surface flows out radially on top of the flowing prism, carrying with it the finer bottom materials which journeyed to the surface. The extent to which the active center of a boil protrudes above the water surface is not readily estimated except by computing the velocity head required to produce the velocities of the radial outflow. In boils which expand to a diameter of 15 to 20 feet these velocities appear to be on the order of two to four feet per sec, corresponding to velocity heads of 0.06 to 0.25 foot. In rivers where bed scour is progressing at a rapid rate the writer, on several occasions, has witnessed the sudden upflow from a boil to exceed half a foot above the water surface. The larger boils in the Mississippi River, which measure from 100 to 300 feet in diameter, have upward thrusts powerful enough to cause large steamers to list noticeably passing

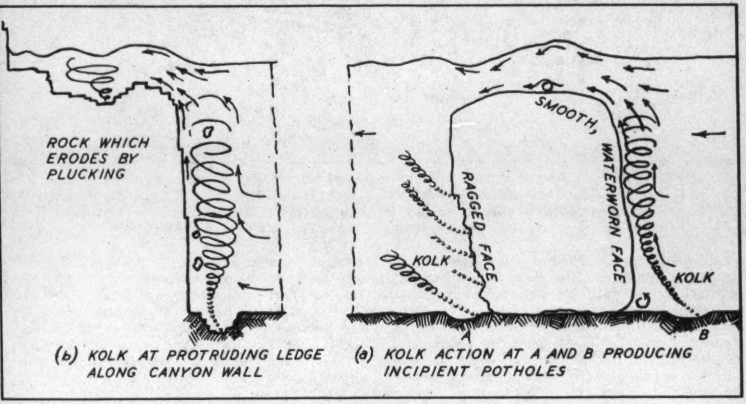


(a) LONGITUDINAL SECTION OF DEEP RIVER SHOWING STRONG KOLK ACTION AT A AND SUCCESSIVE STAGES OF DISSIPATION OF UPWARD PROPELLED WATER AND SEDIMENT INTO A BOIL AT THE SURFACE



(b) KOLK ACTION AS OBSERVED IN SHALLOW CLEAR-WATER STREAMS; SIMILAR TO (a) BUT WEAKER

Fig. 1--Schematic representation of kolk action in sandy-bed streams over them. Although kolk action is probably the most important macroturbulence phenomenon in natural streams, the difficulties encountered in making observations in turbid waters have caused its subsurface mechanics to remain shrouded in obscurity. Its effects on the stream bed, however, are plainly indicative of the nature of the forces involved, and invite comparison with cavitation pitting in turbine blades, pump runners, and ship propellers. WILHELM REITZ [1936] on the Murg River at Graz tried to ascertain its subsurface action by means of a microphone hung over the water surface and was impressed with the clatter of rock particles whenever a boil broke. In the present incomplete state of our knowledge, and in view also of the importance of the kolk in engineering operations, further research into its detailed workings is highly desirable. A good approach is afforded by studying its action upstream and also downstream from a large stationary boulder having fairly vertical faces. Based on the writer's observations, kolk action at such a boulder takes approximately the forms indicated in Figure 2, which also shows the usual location of a pothole in the incipient stage of formation in a ledge-rock surface. The action at the downstream face of such a boulder, as regards reduction of the boulder by stream flow, is far more rapid than that at the upstream side.



(b) KOLK AT PROTRUDING LEDGE ALONG CANYON WALL

(a) KOLK ACTION AT A AND B PRODUCING INCIPIENT POTHOLES

Fig. 2--Kolk action at tall stationary boulders and canyon walls

Vortex action of Type IV trends downward rather than upward, inclining in the direction of local currents around the edges of obstructions such as boulders too large to be moved by rolling. The effects produced are akin to the glistening surfaces of drill holes in rock after blasting has shattered the rock. These smooth grooves have earned the name of fluting and are commonly seen in canyon streams of rapid descent whose flow is of the torrential type. Good observations were made in the Grand Canyon of the Colorado River [MAXSON and CAMPBELL, 1935].

Helicoidal flow at bends was first observed experimentally by JAMES THOMSON [1879] in an eight-inch trapezoidal flume of constant cross-section bent like a letter U and flowing about two inches of water. This experiment, as repeated since by others in laboratory flumes and in river models having strongly exaggerated vertical scales, has become the source of widespread misunderstandings. In natural streams, helicoidal flow occurs in the bends of relatively deep and narrow channels, but not in the wide and shallow channels typical of most streams. Their cross-sections are not adapted to the formation of helicoidal flow (see Fig. 3). The writer has found no indication of helicoidal flow in the Lower Mississippi River. British India engineers report that it does not occur in the Ganges or Indus rivers [CLAXTON]. What does take place according to laboratory tests [VOGEL and THOMPSON, 1933, and FRIEDKIN, 1945] is travel of bedload particles obliquely across the talweg toward the main path of the bed load. It still remains to be definitely established whether this oblique movement is due to entrainment by crosscurrents, or whether the bedload particles are actuated by a hydrostatic pressure differential due to the transverse slope of the water surface over them, which imparts a translatory component to the particles [LEIGHLY, 1934]. The latter supposition is supported by the fact that particles in suspension in the lower portion of the talweg move in concentric paths parallel with the concave bank, indicating no oblique flow. Being in suspension they are not affected by any pressure differentials.

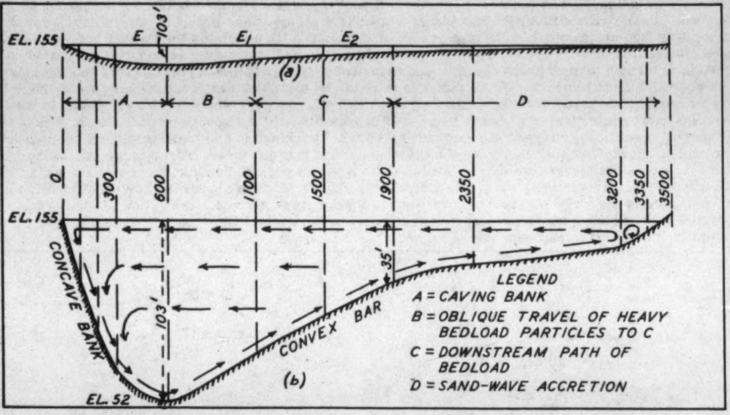


Fig. 3--Cross-section of Mississippi River in bend near Rosedale, Miss., with bank-full flow; (a) undistorted scale, helicoidal flow absent, boats or logs at E, E_1, E_2, do not drift towards concave bank, (b) vertical scale ten times horizontal scale, arrows show helicoidal flow drawn according to James Thomson's flume experiment, 1876

This phase of stream dynamics merits investigation in natural channels, as it affects the principal agency that clears the talweg bottom of bedload. It is a notorious fact readily observed through inspection of dry stream beds that the talweg always presents a literally "swept-out" appearance, except where a rock mass has dropped in too large for the stream's competence to move. It is well established that kolk action performs the role of excavating the talweg in the first place and is the primary agency which causes bank caving [FRIEDKIN, 1945] by undermining the toe of the bank; but the act of clearing the talweg of bedload material divides between traction by the current and, as regards the heavier particles, by the oblique translatory movement referred to, whether ascribed to helicoidal flow or to pressure differential.

The double helicoid described by GIBSON [1909] operates in long straight channels having trapezoidal or rectangular cross-sections. Like helicoidal flow at bends it is seen in high-walled, relatively narrow channels, more particularly in torrential streams. So far as the writer's observations have extended it does not appear to occur in streams having tranquil flow.

Transverse oscillations of the water surface in natural streams, of which superelevation at the concave shores is the outstanding feature, represent another form of macroturbulence which, because of its intangible character, like the kolk, has failed thus far to receive the recognition that is due it. In this case also, small streams and laboratory models, because of their dwarfed manifestations of this phenomenon, have been found of little assistance to engineers and scientists. JAMES THOMSON in [1876] focussed attention on the relation between superelevation and helicoidal flow in a box flume, but the extent to which the swinging of the water surface in a meandering channel affects the stability of the bed and banks has never been properly investigated. Even in the case of the Mississippi where the transverse oscillations are quite marked, paucity of pertinent data has made intelligent study impossible. There is every indication, however, that the oscillations form a definite part of the pendulum swing of the fluid prism in its passage down its channel. The water surface of a sinuous river may well be likened to that of a modern sinuous highway built for fast driving. In the case of a large body of water this pendulum swing represents an assemblage of forces which man cannot curb with conventional types of channel-training works. Superelevation produced by centrifugal force at a river bend reverses and transplants itself downstream. If the frequency of its swings fit the channel curvature, the channel will exhibit more stability than if the channel is straight. If the channel alinement does not fit the periodicity of the swings, disorderly channel conditions usually result.

Utilization of stream-flow energy--All macroturbulence forms represent expenditures of stream-flow energy. During rapidly rising stages when the energy gradient is steepest, this energy reaches maximum values, and at such times streams might be expected to display macroturbulence effects on largest scale. This, however, is not always the case, due to the demands made by load transport. These demands vary widely as between streams, some carrying much heavier loads than others in ratio to their transporting capacity, and vary also within any given stream for a given discharge, depending upon the character and amount of load contributed by its individual tributaries. Load, as here used, connotes any or all of the following: Mineral debris ranging from coarsest to finest, including colloidal gels; dissolved solids; floating debris; ice; and last but not least snow, which produces marked reduction in velocity and in turbulence of all types.

In general, however, the greater the load, the less becomes the display of macroturbulence. During rising stages of the Lower Mississippi its generous display of macroturbulence is not altogether attributable to the magnitude of the stream, but in large part to its comparatively low sediment content in suspension. This ranged from as low as 700 ppm during the rise of the great flood of 1937 when the bulk of the flow came from the Ohio River (which carries a light load), to 3000 ppm when the Arkansas River flood poured in its load [ANONYMOUS, 1939] at a time when the Mississippi was at a much lower stage. In the Colorado River, before the construction of dams, high concentrations of suspended and dissolved solids during rising floods greatly reduced all forms of macroturbulence. The extreme case is seen in mudflows such as occur in desert areas following cloudburst rainfall; a maximum of energy is then consumed in transporting solids and macroturbulence is scarcely in evidence. The opposite extreme is found in sparkling clear-water streams of tranquil flow, whose agitated water surfaces exhibit an array of boils so closely spaced as to set up interferences where their radial outflows meet. In such streams kolk action has every evidence of being a form of dissipation of excess stream-flow energy.

Conclusions--All forms of macroturbulence listed in the tabulation represent expenditures of energy in overcoming channel roughness, which takes many forms. Of these, sinuosity and the alternation of deeps and shoals in the bed are the most important. Microturbulence in natural streams, as in the case of ocean currents [SVERDRUP, 1942], appears to result principally from internal shear and only in small part from contact with, or transmission from, channel roughness or other form of boundary or boundary layer. Surface observations indicate that the size and distribution of microturbulence bodies rising to the surface of a wide and deep river, like the Mississippi are not apparently affected by nearby macroturbulence bodies. The latter, however, plainly show along their peripheries a disintegration into minor whirls dissipating progressively into microturbulence bodies. Vortex action of the upward-flowing kolk type is the most powerful concentrated form of energy at work on stream beds, and is a major agency in scour, bank caving, sediment transportation, and in stream-bed morphology generally. Negative pressure produced by vortex suction of the kolk type appears to be the primary agency which operates in scour by running water, with abrasion produced by entrained sediment particles a contributory agency. The need for research, particularly as regards the mechanics of the suction produced by vortex action, is indicated.

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DISCUSSION

François E. Matthes (United States Geological Survey)--For a number of years past the writer has been making observations on the eroding action of the Potomac River at the Great Falls above Washington and in the gorge below the falls. Although carried on independently and without definite knowledge of the nature of the author's studies on stream-flow phenomena, these observations on the Potomac River have led to closely similar conclusions and in a broad way bear out the essential soundness of the central idea conveyed in this paper on "macroturbulence," which is that the eroding power of a stream resides largely in the concentrated energy of fast-whirling eddies and vortices.

The Potomac when in flood is turbid, and as a consequence direct observation of the flow motions that are active at different points then is impossible; but much can be inferred regarding the character of those motions from the detail sculpture of the rock bed in the gorge and of the channels and intervening crags at the site of the falls, when those features are exposed to view at low water stages.

In that connection the physical properties of the rock materials into which the river is cutting its gorge must be taken into consideration. The country rock is for the most part a hard, massive mica schist that is intruded locally by irregular bodies of igneous rocks of various types. All of these crystalline rocks are cleft by a network of intersecting joints and thus divided into natural blocks, sheets, and slabs ranging in major dimension from less than one foot to several feet, and in places even to tens of feet. Over considerable distance the larger sizes predominate, and since the joints are mostly tight, the rock forms an extremely durable mass that is capable of maintaining steep profiles for a long time. These qualities account for the narrowness of the gorge and the prevailing sheerness of its walls.

The joint fractures, nevertheless, are the principal planes of weakness in the rock, for they are loosened up in the course of time by solution of the cementing minerals and/or by the expansive force of congealing water, and thus the blocks, sheets, and slabs gradually become dislodged and torn out bodily, provided that sufficient force is available.

Now the outstanding characteristic of the craggy rock masses that obstruct the falls of the Potomac and at low stages divide them into several small cataracts, or cascades, is their sharp angularity (see Figs. 1 and 2). These crags, it should be understood, are completely overswept at flood stage by wildly swirling waters, yet they conspicuously lack the rounded and smoothed forms produced by abrasion. It is true that some evidences of abrasion do occur here and there, chiefly on the upstream sides, but they are not conspicuous and not sufficiently prevalent to materially soften the rugged aspect of the rock masses.

Examined in detail, their angularity is seen to be due in general to the salient corners and edges of faceted joint blocks. The re-entrants between the salients also are angular, being bounded by intersecting joint facets, and it requires no effort of the imagination to realize that they have been produced by the bodily removal of joint blocks. To judge from the positions of those hollows, moreover, it is evident that the joint blocks that formerly occupied them were not

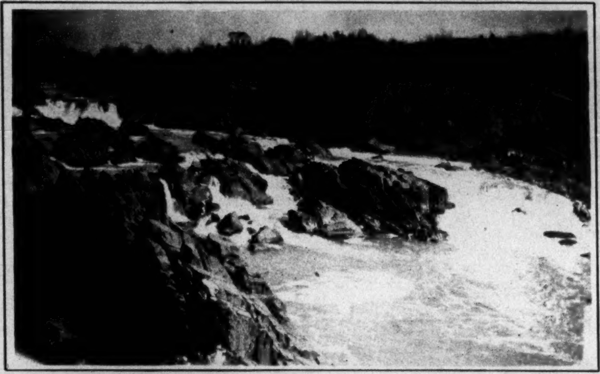

Fig. 1--The main channel of the Potomac along the Maryland side of the Great Falls. The rocks in view are all submerged at flood stage, yet rounded forms due to abrasion are hardly noticeable. The forms are mostly angular and faceted as the result of the bodily removal of joint blocks by the turbulent waters

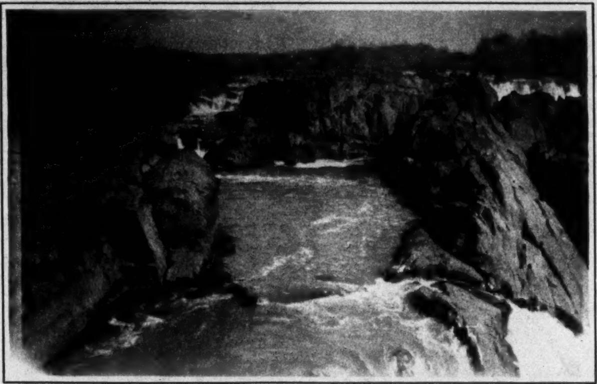

Fig. 2--The channel of the Potomac near the Virginia side, viewed at low stage; Angular, faceted rock forms predominate and show that the channel has not been "worn" by abrasion, but has been literally "quarried" out block by block

simply pushed or toppled over by the onset of swift-flowing water masses, but were wrenched and torn out with twisting motions. This inference regarding the manner in which the blocks were plucked out applies especially to those on the downstream sides of the obstructing rock masses and on their flanks, past which the flood waters rush with tremendous speed. It can hardly be doubted that the plucking of the blocks at those places is done by powerful eddies, or rollers, of type II (2) of the author's classification. Such eddies, the author points out, develop considerable energy at bridge piers, yet bridge piers are specially designed with a view to minimizing their interference with the orderly flow of the stream. Far more intense must be the turbulence created by the angular salients of multifaceted rock masses such as those that obstruct the Great Falls.

All turbulence of rotatory types is initiated, fundamentally, by deflection of the filaments of flow from harmoniously parallel courses at obstructions or irregularities in the channel. Deflection of the filaments in one place inevitably gives rise to convergence in another, and at any point of convergence the filaments arrive with greater force from one side than from the other, and thus a rotatory motion is set up. The greater the velocity of flow and the more abrupt the deflection, the more intense will be the concentration of energy developed in the whirling mass. There is, accordingly, good reason to believe that eddies of type II (2) play a major role in the eroding action of streams. Their importance, indeed, would justify their being designated by a more distinctive term than "eddy," for they are dynamically in a wholly different class from the slow, leisurely eddies that occur in embayments in the channel walls and that are agencies of deposition rather than of erosion. No new term is suggested, but it is desired here to stress the need of one.

Throughout the broad basin at the foot of the Great Falls and throughout the length of the gorge below, angular, hackled rock forms delimited by intersecting joint facets predominate. Rounded and smoothed forms are not wanting, but they are distinctly subordinate. Such forms are restricted, naturally, to rock masses that are so sparsely or so tightly jointed that no discrete blocks can be plucked from them. In some parts of the gorge this type of abrasional sculpture, diversified by potholes of every size and description, is displayed on a grand scale, yet no careful observer, it is safe to say, can pass through the whole length of the gorge without reaching the conclusion that in the main the chasm has been quarried out, so to speak, block by block by the turbulent waters of the river.

One feature of the gorge deserves special mention. This is a small rocky promontory situated on the Virginia side near the lower end of the gorge, about 1 1/2 miles below the falls (see Fig. 3). It juts out obliquely downstream from the wall of the gorge, which immediately above it is nearly straight and very steep, the cliffs descending directly into deep water. Below the promontory, and behind it, there is a spacious cove with sandy bottom in which trees and shrubs have taken root. The promontory rises, by actual measurement, to a height of 45 feet above the low-water line, yet it is overswept by the highest floods. Evidences of recent water wear (abrasion) occur as high as 48 feet.

That the promontory has so long survived in its exposed position is due, undoubtedly, to the fact that it is composed in large part of a more siliceous type of schist than that which makes up the adjoining gorge walls. It is only sparsely jointed and the irregularities in its configuration that are due to the removal of joint blocks have long since become subdued by abrasion to smoothly rounded forms. These characteristics extend all the way to the top. At a height of 40 feet there are fantastic potholes and a sinuous but smoothly worn cross channel one foot wide and two feet deep. Toward the river the rock mass drops off sheer, and at one place there is a nearly vertical wall (marked A in Fig. 3) over 30 feet in height that forms the back of a rectangular recess from which, evidently, a huge joint block was once removed.

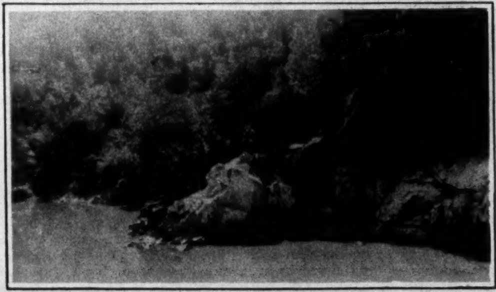

Fig. 3--The promontory in the gorge of the Potomac, viewed from the Maryland side. The highlights on the rock platform to right of center mark approximately the highest level reached by floods, 48 feet above the low stage shown. (A is the 30-foot wall in the recess described; this wall and the flanking rock masses are worn smooth by the bed-load material that is lifted from the bottom of the channel by spasmodic vortices and flung over the top of the promontory)

The most astonishing feature of the promontory, however, is a deposit of coarse gravel and cobbles on its rear, or landward, slope. That deposit does not date from a remote period when the river had not yet cut its gorge to the present depth, but is clearly of very recent origin, for the pebbles and cobbles are fresh and unweathered. Some of them have been deposited within the last few years. All are well rounded and appear to have been transported by the river over long distances. They are typical of the bed-load material as it appears at other points in the gorge. The question therefore arises, by what peculiar action of the river have these pebbles and cobbles been deposited on the rear side of the promontory and at heights ranging from 20 to 40 feet above the low-water level? From a detailed study of the locality the writer concludes that they have been lifted from the river bed by strong currents ascending the sheer cliffs of the promontory and thus literally have been flung over its top. The possibility of these coarse materials, which include many cobbles from nine to 15 inches in diameter, having been swept by currents eddying around the point of the promontory and into the cove behind it is definitely excluded, for those eddying currents are too weak to carry anything coarser than sand.

Proof of the lifting of the cobbles by strong rising currents is abundant and convincing when studied on the spot, but they are not easily described or pictured, for they consist chiefly of rather subtle remodeling effects produced on the cliffs by upward abrasion. Characteristic examples of such remodeling are to be seen on the 30-foot wall in the rectangular recess already mentioned. This wall was originally a joint face and when first exposed must have had angular edges and corners where cut by subsidiary fractures. At two nearly horizontal cross joints there even were overhangs measuring a few inches. Not only are the original rugosities of the wall now largely planed away, but the square-cut edges, corners, and overhangs are rounded off to forms that indicate clearly that they were abraded in upward directions.

Other proofs are afforded by pebbles that have been driven upward into gaping cracks and are jammed in so tightly that even a smart blow will not dislodge them. Some of these wedged pebbles now afford convenient footholds by means of which one can climb down into the rectangular recess and out again.

The ascent of the water up the sheer face of the promontory and its ability to entrain part of the bed load of the river to a height of 45 feet above the low-water level, and presumably 55 to 60 feet above the channel bottom, are probably explained by the combined action of two types of macroturbulence. Jutting out from the gorge wall as it does, the promontory narrows the cross-section of the river channel at flood stage. This circumstance in itself must cause the water to rise at the cliff face, for, as is well known, any marked constriction in a stream channel forces the water to rise at the sides. If the constriction is bilateral, the currents rising at the two sides together with the compensating downward flow in the middle of the channel will form the beginning of a "double helix," or "double spiral," which is the supreme type of turbulence, involving the entire volume of the stream. In the case under consideration, however, the constriction is one-sided, and rising currents occur only at the face of the promontory. There is no evidence of rising currents at the cliffs on the opposite side of the river.

It seems likely, however, that the rising currents at the promontory are supplemented at high flood stages by powerful vortices of type III. Such is to be expected, in the writer's opinion, from the presence of bold obstructing rock masses in the channel directly under the cliffs of the promontory. These obstructions, which at extreme low water are just emergent, probably are not less than ten feet high, and must sharply deflect the rushing waters, thus producing vertical vortices of the spasmodic type. Such vortices would literally suck the pebbles and cobbles up from the bed and whirl them spirally up to the top of the promontory. That the action is spasmodic, brief, and not steadily maintained, is to be inferred from the fact that the deposit of pebbles and cobbles on the rear side of the promontory is scanty and irregularly scattered.

To those interested in the study of stream dynamics, and especially in effects produced by vortices and other types of macroturbulence, the promontory in the gorge of the Potomac is to be recommended as a locality well worthy of a visit.

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PROGRESS IN THE ESTIMATING OF GROUND-WATER SUPPLIES IN HAWAII

Chester K. Wentworth

Abstract--Early development was undertaken without serious estimates of quantities continuously available. Rainfall data have been used as a first approximation to an outside limit. For the Honolulu area ground-water supplies have been estimated by starting with rainfall and subtracting transpiration, evaporation, and runoff, using the best available figures for these. Refinement of this method leads to results that are in conflict with known discharges and suggests that some components of the equation are insusceptible of valid estimate. Statistical analysis of data on rainfall, heads, and discharge offers a more promising avenue to estimates of ground-water quantities. Greatest difficulty, not yet resolved, is the lack of direct measurements on storage quantities in the Ghyben-Herzberg lens, but some progress is being made by indirect methods. Complete solution awaits collection and analysis of data for longer periods.

Development of groundwater in Hawaii by well, tunnel, or shaft has often been undertaken without any attempt to estimate quantities continuously available. Water users have also commonly been misled by the large specific yields from volcanic rocks to overestimate greatly quantities that might be expected in steady operation. And similarly, the copious initial discharge of water from behind impounding dikes has led to far too optimistic predictions of daily or annual water supplies.

The most rudimentary approach, such as use of the most plausible catchment area and an estimate of annual rainfall, yields an outside figure to serve as a safeguard against too sanguine guesses. Common experience does not encourage expectation that steady yield from a given water body can exceed a certain fraction of rainfall over the area from which the groundwater body can plausibly be derived. In Hawaii the recognition of intake areas can generally be accomplished with fair precision: The islands are small, the geologic structure simple, and the topography such that large errors in estimating the amount of the water infiltrated from the surface are not likely to be made. Much larger uncertainties are involved in the query as to how much of the water may be so routed underground as to be subject to capture or draft at a given point or under given conditions.

The problem most pursued in the past 50 years has been that of determining the water supply available to artesian wells in the Honolulu district, from east of Diamond Head to the eastern limit of the distinct Pearl Harbor artesian area. Earliest recourse has been to estimate a mean rainfall over the known total area of watershed and from this quantity subtract amounts estimated for transpiration, evaporation, and runoff. The remainder has been taken as infiltration, of which the major part reaches the remarkable Ghyben-Herzberg lens hydrostatically balanced with sea water. In the Honolulu area the seaward part of this lens is restrained under the artesian caprock formed by impervious rocks of the Honolulu coastal plain, leading to much higher basal water heads and in turn to a much thicker body of fresh water than is common along the larger part of the Hawaiian coast line. At the maximum the fresh water extends more than a thousand feet below sea level.

Earliest estimates of rainfall were based on total watershed areas and on figures for mean annual rainfall that were too high for the total area. Operation of a number of rain gages in the mountainous area during the past twenty years has given us the basis for a fairly valid isohyetal map and a mean rainfall rate. Detailed geologic mapping combined with a more precise discrimination between water barriers and water carriers has resulted in a reasonably accurate delineation of areas of infiltration. Stream gaging has been carried on in Hawaii since 1910 and runoff at the exact positions of gaging stations on certain streams is well established. On the other hand, because of high permeability of rock formations and the variation of rock weathering directly with rainfall, the estimate of total runoff from an area consisting both of unit stream basins as gaged, and spur and foothill areas that are not and cannot easily be gaged, is open to many differences of interpretation.

Rates of transpiration and evaporation have been measured at two stations on Oahu, using grasses as the vegetation cover, and showing large variations with rainfall and situation. No sort of measurement that can be accepted as even a rough sampling of transpiration and evaporation in the rugged topography, with diversified forest cover and variable and varied rainfall, has yet been made, and it is doubted if such measurements can ever be made.

Use of the presumably most valid part of the data mentioned above has in recent years led to infiltration remainders that are materially smaller than the amounts of water actually drawn by pumps from the ground water of the Honolulu sector, with nothing to allow for continued natural leakage. Competent students have come more and more to doubt that a valid estimate of the remainder can be made in this way, owing to the cumulation of unavoidable errors in the estimates of rainfall, areas, and runoff, and particularly of evaporation and transpiration from such mountainous country.

In 1934, an entirely different method of approach was suggested by S. T. Hoyt, in which measurements were to be made of pumpage, rise and fall of heads, and assumptions made that rainfall was normal during certain periods and that amounts of water stored were indicated by head. In these tests account was taken of the four different groundwater areas in the Honolulu sector and the assumption made that there is cross-leakage as well as leakage to the ocean in accordance with head relations. Pumpage and heads were controlled during certain periods to meet certain specified conditions. The data taken during these periods of hydraulic (mechanical) testing were used in a series of simultaneous equations designed to determine quantities of lateral and ocean leakage, porosity and storage volume of each of the component natural basins, and the like.

Although a great deal of useful information on the operating possibilities of the water-supply system was developed in these tests, they failed to yield accurate or even plausible figures for the amounts, leakages, and volumes sought. It is the writer's belief that the chief cause of failure in these tests was their necessarily short duration and the lag in the movement of water quantities corresponding to the heads shown by instantaneous measurement. The equations were based on the assumption of at least approximately completed action and reaction within the period. But it appears that in a hydraulic mechanism such might not be the case.

During the past several years, an attempt has been made to remedy partly the shortcomings of short-period measurements, as well as to develop the cumulative index of infiltration induced by past rainfall which is required in long-term studies. For the latter a good many different functions of past rainfall have been given empirical tests, and instead of using selected short periods, statistical methods have been devised to employ the whole period of reliable records of rainfall, head, and draft. A great many equations have been solved and coefficients determined, some of which have physical significance. Others are of value for purposes of curve-fitting only but can be used as an intermediate step in developing useful data. Progress has been made toward an answer for the practical question of how much water can be had annually from a given sector, but of necessity with increase of understanding comes awareness of certain complications.

Most of these complications involve time. Certain long cycles are involved which are nearly as long as, or perhaps much longer than, the period of adequate recording of data. Some of these are periodic and others are of the decline type, such as the change in storage from the condition prevalent before heavy development to that of the present or of the more distant future. Qualitative prediction can be attempted, but quantitative analysis can only proceed as accumulated data permit cautious extrapolation.

As in the hydraulic tests earlier mentioned, the largest uncertainty inheres in the lag in movement of water quantities. The statistical method has probably resolved some of the shorter-term errors, but longer-term effects must certainly remain in the coefficients derived for any given period. For example, the mean head of fresh water above sea level in the central part of the Honolulu area has been reduced from around 40 feet in 1880 to around 25 feet in 1946. The Ghyben-Herzberg principle, which is firmly established by data at Honolulu, indicates that the depth of fresh water below sea level must, in order to achieve balance with the declining head of the water table, be eventually reduced from nearly 1600 feet to under 1000 feet. By every plausible calculation, shrinkage of the thickness of the fresh water by 600 feet represents a very large amount of water, perhaps of the order of 30 years or more of annual increment to ground water. No matter how such an amount of water is spread and whatever degree of completion of shrinkage is assumed, the amounts derived from this source can well constitute a large error in the calculation of annual water supplies by empirical methods.

Direct measurement of shrinkage in amounts of the deeper fresh water has not yet been made but will eventually be accomplished. Data now available and methods of calculation now in use permit an approach to evaluation of the annual variations of rainfall, draft, and more immediate storage at the water table. They encourage formulation of the problem of lagging yield derived by shrinkage of the Ghyben-Herzberg lens, but the period of reliable data is probably still too short to permit a valid determination of the rate of such yield or of its probable duration. While such yield is in progress, or at any rate, while lowering of head is still in progress, only rough and somewhat subjective estimates can be made of the increase in amounts of annual water supply which might be accomplished by reduction of natural leakage.

On the one hand, because of the small rather definite areas involved and the short distances and short periods of separation between source and output points, estimation of water quantities at Honolulu may appear somewhat simple. Indeed, moderately valid figures for water quantities have long been available. However, because of the short time relationship between rainfall fluctuations and supply fluctuations, somewhat precise estimates and close vigilance are needed to guide practical operations.

On the other hand, because of the extraordinary qualities and behavior of the thick Ghyben-Herzberg lens at Honolulu, the refining of estimates of annual quantities beyond the first approximation is extremely difficult and, even with improved comprehension of the hydraulic mechanism, can proceed only so rapidly as the duration of recorded data becomes commensurate with the length of various cycles of its behavior. Because of present incapacity to measure the declining amounts of water in the lower part of the Ghyben-Herzberg lens, differences of opinion on the question of what some believe to be excessive draft are not at present resolved by simple quantitative data. Under these conditions and with the legal and financial complications inherent in the overlaps between public and private use of water supply, only a beginning has been made toward a unified system of regulation of water use. Chief steps in this direction consist of gradual improvement of measurements and the recording and analysis of data, in order to develop a working estimate of quantities consistent with the span of data available.

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EROSIONAL PHENOMENA ASSOCIATED WITH VOLCANIC ERUPTION OF PARÍCUTIN, MEXICO

W. C. Lowdermilk

A study of erosion and aqueous transportation of volcanic ash at Parícutin--Spectacular erosion of volcanic ash in the vicinity of the Volcano and its damaging effects downstream in the Los Reyes Valley were reported by William F. Foshag, Kenneth Segerstrom, and others, which led to recommendation for a study under the auspices of the National Research Council of the United States and the Comision Impulsora y Coordinadora de la Investigacion Cientifica of Mexico. Upon approval of the project, plans were perfected for a preliminary field study on and about the Volcano during the month of August 1945.

José Navarro y Samano and Manuel Sandoval Vallarta, with a car, were assigned by Lorenzo R. Patiño, Jefc del Departamento de Conservacion de Suelos of Mexico, for collaboration in the study with W. C. Lowdermilk of the Soil Conservation Service and Reed W. Bailey of the Forest Service of the United States.

Field work was carried on from August 1 to 23, 1945. In addition to the car supplied by the Departamento de Conservacion of Mexico, the United States Geological Survey loaned a pickup truck which was in Mexico at the time. These facilities expedited field work.

The volcano of Parícutin occurred in the upper drainage of the Itzicuaro, a small stream flowing westward into the Los Reyes basin-like valley and thence into Rio Márques, thence into Rio Balsas that reaches the Pacific Ocean in the Bahía de Petachalco.

Field studies included the running of general transects across the upper valley of the Itzicuaro at selected intervals. A trip was made downstream into the open alluvial plain of Los Reyes, where irrigation of sugar cane, which is the chief enterprise of this picturesque area, had been interrupted by floods highly charged with volcanic ash eroded from the vicinity of Parícutin Volcano. Besides this general plan, observations and measurements were made of sites where characteristic phenomena of mass movement, rilling, gullying, and flood flows were encountered. Samples of fresh ash and underlying soil, derived from old weathered ash of former eruptions, were collected by the field party and analyzed under the direction of Lorenzo Patiño.

The deposit of ash about the Volcano was laid down in an area of elliptical form, elongated toward the west. Depths vary from ten feet and more near the Volcano to traces some 200 miles away. Ash in depths of six inches or less did not destroy or smother vegetation, for ground vegetation grew up through the ash as it fell and kept its general vigor. Greater thicknesses of ash, especially of 12 inches and more, generally had smothered out ground vegetation and weighed down branches of trees, changing the face of the landscape in important ways and changing the hydrology and the regimen of erosion of the area.

Extraordinary erosional phenomena in the ash were most conspicuous in an area about 15 miles long and less than ten miles wide. Here erosion rills mark surfaces of slopes in a spectacular manner. These surfaces display, in miniature, a wide range of land sculpturing phenomena, such as consequent valleys, stream capture, and cut and fill with changes in grades. Rills coalesce to form gullies that, in many cases, have cut through recent deposits into the underlying prevolcanic surface. With marked flattening of channels, ash has been deposited to form broad outwash fans. Ash was spread out on old valley floors in remarkably smooth surfaces. Shallow braided channels spread across such surfaces, as was observed in action. Concentrated flows cut through such deposits deeply into underlying surface material. On the slopes of Conijuata, mass movement of ash was in progress as the toe of the slope was cut away by a great gully. Trees standing in several feet of ash were being tilted down slope at different angles from the perpendicular and showed relative movement. Mud flows in the ash were observed only on a small scale. During rains, local ground water built up in the ash to the surface on slopes and burst forth into small mud flows. On reaching the flatter areas, these flows spread out into a thick slow-moving mass of material.

Storm flows of suspended loads were observed and sampled in two heavy storms. In the first sample, silt measured from 39.32 to 52.62 per cent by weight. In samples taken of a much larger stream of another storm, percentages of silt varied from 64.14 to 65.22 per cent by weight. These samples contained from 0.26 to 0.98 per cent of coarse gravel, from 65.7 to 72.1 per cent of sands, from 18 to 22.3 per cent of silt, from 7.8 to 12.8 per cent of total clay, and from 5.8 to 9.8 per cent of colloidal clay.

Fresh ash contained a strikingly large percentage in the clay fraction, from 3.14 per cent to 12.8 per cent. Of these fractions, colloidal clay made up more than 50 per cent of the total clay. It is this fine material that is suspected of being responsible for changes in infiltration rates of the ash, and in causing heavy runoff in storms. Fine colloidal dust of ash material stays in suspension in the air for long periods of time, following Stokes's Law, and is brought down chiefly by rains and tends to seal the surface against rapid infiltration.

This sorting action of volcanic ash particles in their fall may play an important role in changing the regimen of runoff and erosion. Profile sections through the ash disclosed layering with varve-like effects of alternating layers of coarse- and fine-grained ash particles. Erosion proceeded in step formations; especially in head cutting. Further study of this aspect of ash fall is indicated.

Hydrology of the Itzicuaro drainage was changed in important ways by the fall and deposit of ash over the headwaters. Spectacular erosion rills and gullies occurred throughout the area of deposit that smothered out the ground vegetation. Aerial photographs of the area before the Volcano occurred do not show rills and gullies in the land surface. The contrast between aerial photographs before and after the ash fall is striking evidence of a remarkable change in physiographic processes.

Smothering of ground vegetation and its layer of litter and the breakage of branches of trees doubtless reduced the rate of transpiration loss of water from the soil. But evaporation loss from the wetted ash surface may be higher than that from the former ground surface. The differential in disposition of rain waters as well as sealing action of bare ash may account for a higher runoff coefficient than under pre-volcanic conditions.

The ash fall when sufficient to smother ground cover and vegetation creates a bare surface of ash sorted into layers by differential rates of fall and by rain action. This new raw ash surface contains a striking amount of colloidal material that is believed to vary the rates of intake of rain sufficiently to modify runoff coefficients. The lack of cohesive agencies as exist in natural soil leaves the ash in a single grain structure. Streams pick up suspended loads of fine particles in thin flow and larger material as currents gain volume and velocity. The resultant effects on sloping surfaces are the formation of rills in a spectacular manner and cutting of deep gullies into the ash fall and underlying surfaces. The quantity of ash and eroded underlying material reaches high suspended loads. Samples measured up to 65 per cent by weight.

Storm runoff with heavy suspended loads takes on characters different from that of clear water streams, especially in density wherein hydraulic forces change rapidly. Densities of as much as 2.00 are recorded. Flows of such densities have unusual destructive powers, and destroyed diversion dams at the intake of the Los Reyes Valley irrigation project.

It is estimated from measurements of ash removal that at the time of the study about one-third of the ash on slopes had been moved, some was deposited in valley floors and some carried in streams farther down the drainage.

Control of base levels of cutting should have a decisive effect in reducing progressive erosion. Permanent check dams built at strategic locations to raise base levels would, it is believed, exert an effect that would gradually grow updrainage and bring on the deposition of ash that otherwise would continue to erode for years to come.

But generally measures to reduce the excessive erosion of the ash will be of little general effect until a covering of vegetation spreads over the ash surface. Examples of the effect of a fall of pine needles on the ash were found to reduce erosion of the ash promptly.

The ash fall about the new Parícutin Volcano has caused marked changes in action and degree of physiographic forces. This reconnaissance study indicates the desirability of further study of these modified processes and their effects.

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ESTIMATING STORM-WAVE CONDITIONS IN SAN FRANCISCO BAY

J. A. Putnam

Introduction--Wave action is usually associated with navigation operations on the open sea and with construction problems relating to shore and beach protection. However, there are many problems which involve waves generated by wind on relatively small bodies of water. Some of these problems include small craft anchorages, berthing and docking operations, and erosion by wave action of the upstream face of dams at reservoirs.

In San Francisco Bay, fairly strong winds blow generally in the direction of the long axis of the Bay during storms, thus acting on the water over distances of the order of 30 miles. This distance, hereinafter called the fetch, is sufficient to generate waves of the order of eight or more feet in height. In the region opposite the Golden Gate, wave conditions may be further complicated by ground swell entering the Bay from the open sea. The following discussion will be confined to wind waves generated by storm winds in San Francisco Bay. The method of analysis is applicable to other bodies of water, large or small. In fact, the method is an adaptation of wave-forecasting procedures developed during the last three years, largely as the result of research for the Bureau of Ships and the Hydrographic Office, United States Navy Department, by H. U. Sverdrup and Walter Munk of the Scripps Institution of Oceanography of the University of California, by the Department of Engineering, University of California, and by the Woods Hole Oceanographic Institution. Much useful work has also been contributed by the Admiralty Research Laboratory and other British Army and Navy organizations.

Generation of waves by wind--A wave is described by its length, L, that is, the horizontal distance from crest to crest or trough to trough, by its height, H, that is, the vertical distance from trough to crest, and by its period, T, that is, the time interval between the appearance of two consecutive crests at a given position. Complete details relating to fundamentals of waves may be found in publications by the SVERDRUP and MUNK [see "References at end of paper, in press] and the BEACH EROSION BOARD [1942].

Waves are generated by the pushing and pulling action of the wind on the water surface, and always travel in the direction toward which the wind blows. In general, the longer, farther, and faster the wind blows, the higher will be the waves and the greater will be their period, wave length, and velocity. The push of the wind results from aerodynamic forces generated by the relative velocity between the wind and wave crest, and depends upon the form of the crest. The wave receives energy from the wind when the wind velocity exceeds the wave velocity. Eventually, the waves may travel faster than the wind, and energy is then given up by the waves.

The pulling action is due to the tractive force resulting from the relative velocity between water particles and the wind. Experiments and field observations indicate that water particles move in orbits which overlap with a resultant mass movement or transport in the direction of wave progress. The particle velocity at the wave crest in the direction of the wind exceeds slightly the particle velocity at the wave trough in the direction opposite to the wind. The result is a net transfer of energy to the water by the wind, regardless of whether or not the wave velocity exceeds the wind velocity. However, the net energy transfer to the waves from the wind is greatly reduced when the waves move faster than the wind, with the result that the height of the waves in feet does not exceed about 1/40 of the square of the wind velocity in knots, regardless of how long the wind blows or how great the fetch.

Within the generating area, steep, short-crested waves of all possible heights, lengths, and periods are present, many of them breaking as white-caps. The largest waves will be those which have traveled the greatest distance and have therefore been acted upon by the wind for the longest time.

Some idea of this variability in wave length and crest length may be obtained by examination of Figure 1, which is an aerial photograph taken from an altitude of 3000 feet above the water surface of waves at the end of a fetch of 4.9 nautical miles at Clear Lake, California. The average wind velocity at the time the photograph was taken was approximately 12 mph. A series of such photographs was analyzed for wave length and crest length, and the results are presented in Table 1 and in Figures 2 and 3.

Fig. 1--Waves due to 12 mph wind, showing variability in wave length and in crest length

Table 1--Variation of wave length and crest length with length of fetch

Photo number	Time of photo	Depth of water	Fetch	Wave length			Crest length		
				Number of waves	Mean of all waves	Mean of longest 30 per cent	Number of waves	Mean of all waves	Mean of longest 30 per cent
	h m s	ft	naut mi		ft	ft		ft	ft
6	17 11 18.10	7.5	5.04	250	19.2	23.9	108	60.0	84.5
8	17 11 24.00	16.5	4.86	407	18.8	23.7	120	57.6	80.0
10	17 11 30.00	18.3	4.67	303	18.8	23.2	120	54.6	74.6
15	17 11 45.00	20.1	4.19	306	17.1	21.3	101	53.2	73.8
20	17 12 00.00	20.1	3.50	422	14.3	18.6	103	46.3	62.5
25	17 12 15.00	18.8	2.87	444	10.9	14.0	130	41.9	61.2
30	17 12 30.00	15.7	2.25	492	8.6	10.5	110	41.0	57.9
33	17 12 39.00	14.0	2.04	446	7.0	8.6	139	33.6	45.9
34	17 12 42.00	13.5	1.93	448	6.6	8.2	100	32.8	45.6
35	17 12 45.00	11.0	1.79	314	6.0	7.4	150	31.8	45.7

The graphs shown in Figures 2 and 3 are based on Figure 1 and are typical of all the photographs analyzed. These figures illustrate the type of variation to be expected in the characteristics of actual waves. Although detailed data on wave heights were not obtained in this study, other observations indicate a similar type of variability for wave height. The forecasting charts described below are based upon the mean of the highest 30 per cent of the waves present at any one time in a given area. In order to determine the highest 30 per cent from field observations, it would be necessary to observe the height of every wave passing a given point (such as a staff gage) for a period of approximately ten minutes and then tabulate the heights of the highest 30 per cent. The mean or average of this tabulation would then correspond to the wave height of the forecasting charts.

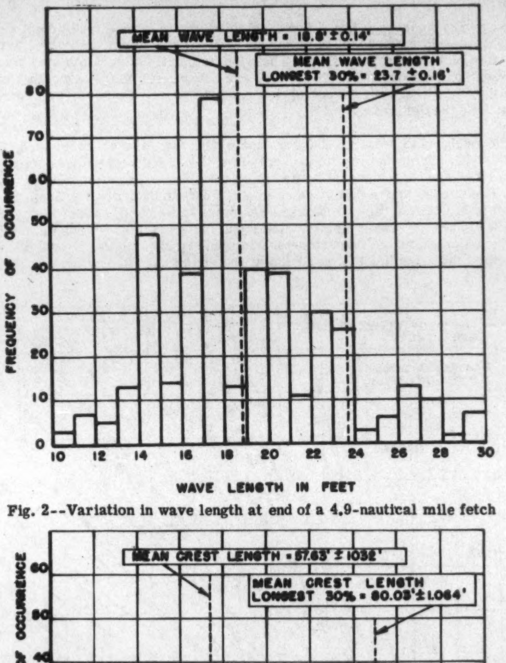

Fig. 2--Variation in wave length at end of a 4.9-nautical mile fetch

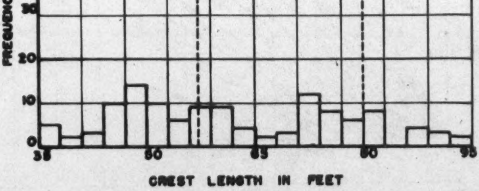

Fig. 3--Variation in crest length at end of a 4.9-nautical mile fetch

On the basis of the rate of energy transfer from the wind and the rate at which the wave energy advances, it was possible to establish a differential equation from which the relationships between the waves and wind velocity, fetch, and duration (length of time wind has blown over a given fetch) could be obtained as special solutions. Three numerical constants were involved which were evaluated in terms of all known observations and empirical relationships. The results have been presented in the form of graphs [SVERDRUP and MUNK, in press].

Knowing the wind velocity, fetch, and duration, it is possible to read off, from these charts, values of average wave height and period of the highest 30 per cent of the waves present at the end of the fetch. The maximum wave height will be approximately 1.6 times the average height.

Application to San Francisco Bay--For a selected site at which wave height and period are desired on a land-locked water body, the fetch is fixed for any given wind direction and may be scaled from a map or hydrographic chart. The wind velocity and duration may be obtained from United States Weather Bureau records of hourly wind observations. The weather stations should be so selected that they best represent the wind conditions over the water approaches to the point for which wave data are desired.

Knowing the fetch, wind velocity, and duration of the wind, the corresponding wave height and period may be obtained from the charts presented by SVERDRUP and MUNK [in press]. However, these charts are designed for forecasting waves on the open sea and are not convenient for small water bodies. The curves presented in Figures 4 and 5 have been derived from those of the Scripps Institution of Oceanography and have been found to be much easier to use. Figure 4 shows wave height as a function of wind velocity, wind duration, and fetch. Presentation of curves of constant fetch and constant duration as parameters in these figures makes it possible to determine at a glance whether the wave height and period at the end of the generating area are controlled by fetch or by duration.

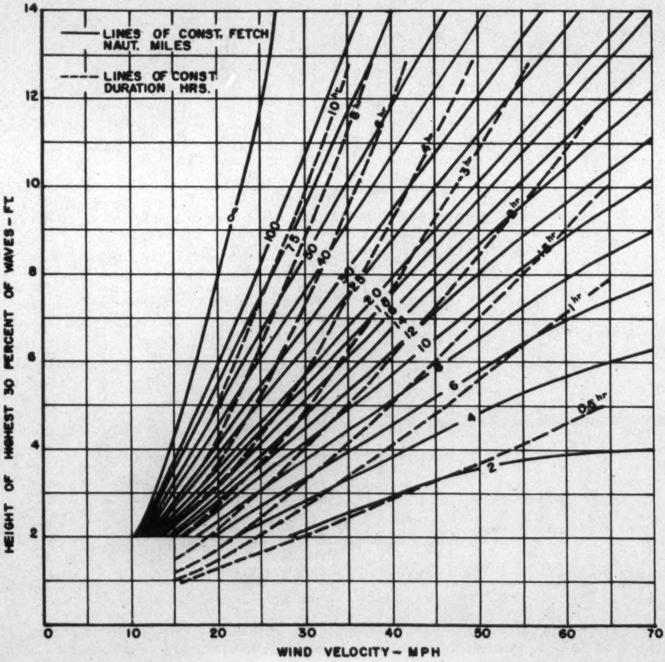

Fig. 4--Wave height as function of wind velocity, wind duration, and length of fetch

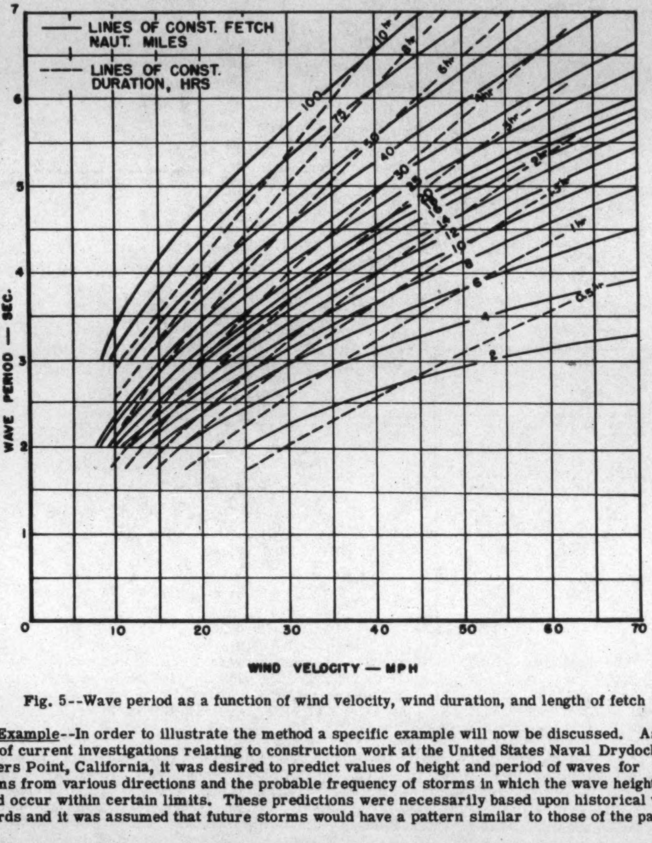

Fig. 5--Wave period as a function of wind velocity, wind duration, and length of fetch

Example--In order to illustrate the method a specific example will now be discussed. As a part of current investigations relating to construction work at the United States Naval Drydocks, Hunters Point, California, it was desired to predict values of height and period of waves for storms from various directions and the probable frequency of storms in which the wave height would occur within certain limits. These predictions were necessarily based upon historical wind records and it was assumed that future storms would have a pattern similar to those of the past.

Figure 6 shows the wave-generating area with respect to Hunters Point. The wind records for Oakland Airport were analyzed because it was believed that the winds in this area would best represent the conditions for the water approaches to Hunters Point. Selected storm winds were then checked against the corresponding records for Hamilton Field and San Francisco Airport. The data indicate in each case that the movement of the air masses was uniform over the fetch. All westerly winds from northwest to southwest were excluded, since this region is occupied by the San Francisco Peninsula. Since waves of less than four feet in height were unimportant in this investigation, most of the winds of less than approximately 25 mph in velocity were not considered. For this velocity, waves exceeding four feet in height cannot be developed in the available generating area, even though the wind should persist indefinitely.

Figure 7 illustrates the manner in which the available hourly wind data were plotted. The direction of the wind is indicated by the small arrows shown at various points along the graph. For

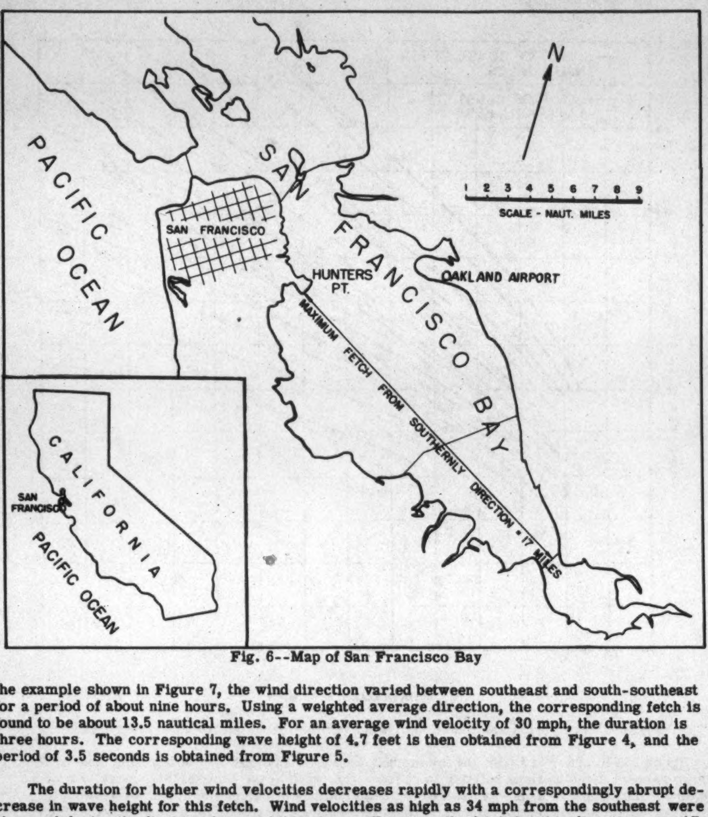
N
1 2 3 4 5 6 7 8 9
SCALE - NAUT. MILES
PACIFIC OCEAN
SAN FRANCISCO BAY
SAN FRANCISCO
HUNTERS PT.
OAKLAND AIRPORT
MAXIMUM FETCH FROM SOUTHERNLY DIRECTION = 17 MILES
CALIFORNIA
SAN FRANCISCO
PACIFIC OCEAN

Fig. 6--Map of San Francisco Bay

the example shown in Figure 7, the wind direction varied between southeast and south-southeast for a period of about nine hours. Using a weighted average direction, the corresponding fetch is found to be about 13.5 nautical miles. For an average wind velocity of 30 mph, the duration is three hours. The corresponding wave height of 4.7 feet is then obtained from Figure 4, and the period of 3.5 seconds is obtained from Figure 5.

The duration for higher wind velocities decreases rapidly with a correspondingly abrupt decrease in wave height for this fetch. Wind velocities as high as 34 mph from the southeast were observed during the first two hours of this storm. However, the fetch for this direction was 17 nautical miles, and the duration was not sufficiently long to generate waves that exceeded the values shown above.

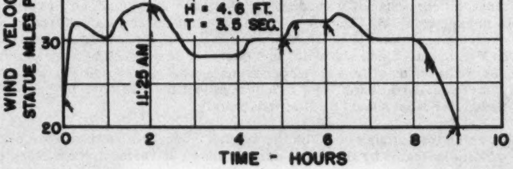

Fig. 7--Typical record of wind velocity and direction for Oakland Airport

In so far as is known, measurements of wave height and period have not been made at Hunters Point during the recorded storm periods. However, Table 2 is based upon observations made on two occasions since the investigation was made.

Table 2--Measurements made on two occasions since the investigation

Date	Velocity	Direction	Height		Period	
			Observed	Calculated	Observed	Calculated
	stat mph		ft	ft	sec	sec
April 2, 1945	21	north	2.5	2.8	2.8	2.8
December 27, 1945	23	south-southeast	2.9	3.2	3.2	2.9

The discrepancies between observed and calculated values are within the observational errors.

Conclusion--The wind-wave relationships developed during recent years for forecasting waves on the open sea have been shown to apply with reasonable accuracy to small land-locked water bodies. The method may also be expected to apply to small reservoirs and to larger bodies of water, such as the Great Lakes. For the latter, however, the wind conditions may be comparable to those on the open sea, and it would appear that suitable weather maps might be required for determining wind velocities and fetches.

Little is known of the effect of islands, headlands, and shoals on the predicted wave characteristics, when these are present in the generating area. Much valuable information relating to these effects could be obtained at reasonable cost by establishing automatic wave-recording stations at a few well-selected points in a body of water such as San Francisco Bay.

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DISCUSSION

Harry W. Oliver (Pacific Gas and Electric Company, San Francisco, California)--What effect has the incoming and outgoing tide upon the wave heights and lengths, that is, when blowing with or against the tide?

R. C. Farrow (Water Rights Branch, British Columbia Government, Victoria, B. C.)--Is there some limiting minimum depth for which the method is applicable?

M. P. O'Brien (University of California, Berkeley, California)--So far as generation of waves is concerned, I think the effect of the tide would be simply the addition of that much velocity to the velocity of the wind--in other words, two or three knots added to the wind would take care of generation.

A second item would be the effect upon waves generated in still water and then transmitted against a strong current: They would be shortened and get somewhat higher. Or if they ran into a current moving in the same direction, would they be longer and flat? There are really two types of problems when measuring wind velocity and the effect of the tidal current.

As to the effect of depth, of course, the waves are growing along the fetch, so the ordinary criterion of depth, half a wave length giving deep water, doesn't apply over the entire fetch. Deep water is something like half, or as little as 0.3 of the wave length. The only significance of Hunters Point in this problem is that it afforded deep water. Around Hunters Point the water is well over 40 feet in depth.

A further point about these equations, which might be appreciable for lakes at high altitudes, is the effect of air density in the generation of the waves. All our work has been about sea-level conditions; we have never studied the difference density would make at an altitude of 10,000 feet on the generation of waves in a small reservoir.

J. A. Putnam--With regard to Oliver's question, where there is a relatively restricted area, there will be a refraction effect. A current setting against the wind or wave progress would cause the waves to be higher. On the other hand, if the tidal current moves in the direction of wave progress, the waves tend to be somewhat lower. In San Francisco Bay, particularly at the southern end of the Bay, tidal velocities approach four knots and have but small effect. The effect would be well within the observational errors of the method now available for determining wave characteristics from wind data.

With regard to O'Brien's comment, maximum wave height was one of the problems of interest in the Hunters Point development. On the basis of storms in the past, it is possible to have highest waves of the order of 8.5 feet generated over a fetch of approximately 17 miles.

Answering Farrow's question, much of the wave phenomena discussed here will depend upon so-called "deep-water" conditions, and there is no hard and fast dividing line, or critical depth. Under usual circumstances, deep-water conditions prevail when the depth exceeds one-half the wave length. For true shallow-water waves, the depth must not exceed one twenty-fifth of the wave length. There is an intermediate region of transition which requires further investigation in so far as wave generation is concerned. For the particular problem we were concerned with at Hunters Point, we had a maximum period of around 3.7 seconds, with a corresponding wave length of the order of 70 feet. Thus deep-water conditions prevailed in all regions where the depth exceeded 35 feet.

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SOME RECENT EVAPORATION INVESTIGATIONS

Arthur A. Young

Little can be done toward prevention of evaporation from water surfaces, but much has been learned from investigations that can be useful in estimating evaporation losses. In the aggregate such losses are tremendous and are increasing in proportion to the areas flooded by the construction of additional reservoir systems. With the objective of adding to the general knowledge of the subject, the Division of Irrigation, United States Soil Conservation Service, has made a series of studies in Southern California. These cover: (1) Determination of reduction coefficients for several commonly-used evaporation land pans; (2) development of a special screened pan having a coefficient that approaches unity; (3) effect of colored pans and of salt solutions on evaporation losses; and (4) some limited evaporation studies at lakes and reservoirs.

An evaporation coefficient is defined as a ratio for the conversion of evaporation from a given body of water to equivalent evaporation from another volume of water differing in area or depth. Coefficients are useful for conversion of known evaporation from an evaporation pan to equivalent evaporation from a lake or reservoir. They are used also for reduction of evaporation from a small pan to evaporation from a large pan or from one type of pan to another of different characteristics. It is the common method of estimating reservoir evaporation from pan records.

The pan studies were made during the five-year period 1935–1939, inclusive, at the Division of Irrigation's Fullerton Station in Orange County, California. This was on the Coastal Plain about ten miles from the ocean in an open, flat area where there was little obstruction to wind. The mean annual temperature was 60 degrees, the relative humidity about 68 per cent. Thin fogs are common in this area during summer months. Wind velocity, 20 inches above ground surface, averaged 2.8 mph. Rainfall averaged about 13 inches annually, falling exclusively during the winter.

Evaporation coefficients--The principal study at the Fullerton Station was determination of pan coefficients relative to evaporation from a 12-foot diameter pan, three feet deep, set 33 inches in the ground with water surface in the pan approximately coincident with the ground surface. Previous experience with a 12-foot pan and an 85-foot diameter shallow reservoir by **SLEIGHT** [see "References" at end of paper, 1917] and **ROHWER** [1931] in Colorado indicated only small differences in seasonal evaporation losses from the two water areas, leading to the conclusion that for diameters greater than 12 feet the size of the pan has little effect on the evaporation. Most investigators, however, stipulate that coefficients are most reliable when used under exactly the same meteorologic conditions that existed at the time and place where they were first determined.

Based upon evaporation from the 12-foot pan, coefficients were found for a number of sunken ground pans of various diameters, a Bureau of Plant Industry pan, a Weather Bureau Class A pan, a Colorado square pan, and a specially-designed screened pan. The ground pans, including the special screened pan, were circular, of the specified diameter, each three feet deep and set in the ground 33 inches. The Bureau of Plant Industry pan was six feet in diameter by 24 inches deep, set 20 inches in the ground. The Colorado type pan was three feet square, 18 inches deep, and set 14 inches in the ground. In each pan the water surface was held approximately at ground level. Rim heights above ground level were thus four inches for the Bureau of Plant Industry and the Colorado pans and three inches for each of the other pans. The different tests covered periods ranging from two to five years.

The Bureau of Plant Industry pan has been used in western states since 1907, principally in connection with plant studies by the Department of Agriculture, and many of its earlier records are published in the Monthly Weather Review. The evaporation is slightly more than from the 12-foot pan because of difference in size, depth of water, and extent of rim exposure. Coefficients for the conversion of evaporation from the Bureau of Plant Industry pan are more uniform throughout the year than those for smaller pans or those more exposed to the elements. They show a monthly range of 0.92 to 0.96 with an average of 0.94. Such uniformity is possible principally because of the generally close agreement in water temperatures in both pans.

The Weather Bureau Class A pan has been in use at many places in the West with the earliest records beginning about 1916. This pan is principally of value because of the large number of records in existence, of which at least 50 are in California. Exposure of the pan above ground results in the highest rate of loss of any pan in general use. Annual evaporation from the pan is proportional to annual evaporation from a larger body of water where there are similar meteorologic conditions, but the monthly ratios are certain to vary because of the greater heat storage in lake or reservoir. Monthly evaporation from sunken ground pans is slightly more consistent with reservoir loss than Weather Bureau pan evaporation.

The mean annual coefficient obtained for the Weather Bureau pan in this study was 0.77 as compared with 0.70 in Colorado. Results were consistent throughout the five-year test. In view of the difficulties of measurement of evaporation from large water areas and the relatively small differences between the values of coefficients obtained in the intermountain and Coastal areas, a coefficient applicable to an intermediate area, between the values of 0.70 and 0.77, should be sufficiently accurate in most cases.

The Colorado square pan was first used at the Colorado Agricultural Experiment Station about 1890, and, with exceptions, evaporation measurements have been continued to date. This pan appears to have the longest record of evaporation known in the western states. Annual evaporation from the Colorado pan, according to California experiments, is nearly the same as that from a four-foot diameter pan three feet deep, set in the ground.

The coefficient for conversion of evaporation from a Colorado-type pan to evaporation from a 12-foot pan averaged 0.89 for a five-year period, as compared with values of 0.78 obtained in Colorado [ROHWER, 1934]. Differences in design and particularly in height of rim above ground and water surfaces account for the different coefficients.

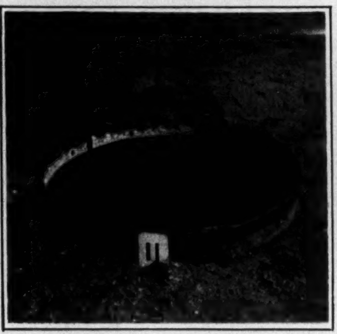

Fig. 1--Screened pan, diameter two feet, depth three feet, set 2.75 feet in ground. The screen is 1/4-inch mesh hardware cloth stretched in a wire ring. (Measurement is made with a hook-gage in an outside stilling well; reduction coefficient averages 0.98)

The screened pan (see Fig. 1) presents a departure in design from other pans in that a horizontal screen is suspended midway between the rim and the water surface. This pan is two feet in diameter by three feet in depth, set 2.75 feet in the ground with the water surface maintained at ground level. The screen is made of 1/4-inch galvanized hardware cloth enclosed in a stout wire ring slightly smaller than the diameter of the pan. It prevents interception of a portion of the solar energy during the day and decreases back radiation at night, thus maintaining a more uniform water temperature than would exist without the screen. In the four years of measurement, from 1936 through 1939, annual evaporation from the screened pan was about two inches greater than from the 12-foot pan, whereas without the screen the difference would have been 12 inches. The annual coefficient is 0.98, only slightly less than unity, the annual loss being very nearly equal to the annual loss from a reservoir similarly located. Monthly coefficients, however, are variables, changing from month to month, and are higher in summer than in winter. Tests with this pan have been made for several years under various conditions ranging from coastal to desert locations with consistent results. The benefit of using the screened pan lies in its low annual evaporation rate, which makes an annual coefficient unnecessary.

Coefficients resulting from these studies are listed in Table 1 [YOUNG, 1945]. These values were developed in a semi-arid region without winter freezing and are presumed to be applicable for similar areas elsewhere. At present it is impossible to outline with any degree of accuracy regional areas wherein the California coefficients are most applicable and other areas where similar coefficients developed in Colorado should be used. Probably a broad distinction should be made between western and southwestern states where winters are short and mild and the intermountain region where temperatures are low. Between these extremes lie intermediate areas for which intermediate values may be assumed.

Table 1--Coefficients resulting from studies over a four-year period under various conditions

Size or type of evaporation pan	Coefficient ratio
Circular pans, each three feet deep, set in the ground	
12-foot diameter	1.00
6-foot diameter	0.91
4-foot diameter	0.89
2-foot diameter	0.81
1-foot diameter	0.66
Weather Bureau pan	0.77
Bureau of Plant Industry pan	0.94
Colorado pan	0.89
Screened pan	0.98

Table 2--Evaporation from pans of various colors compared with evaporation from new galvanized pan

Color of pan	Per cent of evaporation from new galvanized pan
	pct
White	82.7
Orange	92.0
Light yellow	93.3
Aluminum	97.6
Galvanized, new, light-weight metal	100.0
Dark blue	101.6
Dark green	102.5
Black	105.7
Galvanized, old, heavier metal than new pan	105.9
Copper	106.7

Effect of color on evaporation pans--Evaporation pans are made of unpainted galvanized iron and only occasionally is any other type used, although published reports have described some that are painted black or made of copper. More often they are brightened by the use of aluminum paint. To determine the effect of such treatment, seven pans were covered inside and outside with different colored enamel paint, one was made of copper, and two pans were left unpainted, one being made of new and light-weight galvanized iron and the other of old and heavier metal darkened with age. Aside from aluminum paint on one pan, colors ranged from white through light yellow, dark green, dark blue, and orange to black. All pans were two feet in diameter by ten inches deep set on two-by-fours on the ground surface and had similar exposure. The water surface varied from two to three inches below the rim. Tests continued for 11 months.

Assuming total evaporation from the new galvanized pan to be 100 per cent, loss from other pans is shown in Table 2. This tabulation shows only the effect of color on pans of the size demonstrated, and there is no assurance that they apply exactly to larger pans.

Results obtained from this test show that paint should not be applied to evaporation pans if comparable results are to be expected. The reduction of 2.4 per cent owing to use of aluminum paint is relatively small. A similar test, previously unreported, made at another time and place, showed loss from an aluminum painted pan to be 9.2 per cent less than from a similar galvanized pan. The difference in the two tests probably resulted from use of different brands of paint, one of which was brighter and more reflective of heat than the other. The use of aluminum paint on evaporation pans, applied for the purpose of keeping them clean, decreases heat absorption with a consequent reduction in evaporation. Table 2 also shows greater evaporation from an old, darkened pan than from the new galvanized-iron pan. The unpainted copper pan had greater loss than any painted pans, as would be expected from its high thermal conductivity.

Effect of salt solutions on evaporation--The effect of salt solutions on evaporation is of some interest because of the number of salt lakes in western states. Salton Sea in California, Great Salt Lake in Utah, and lesser bodies of saline water in the Great Basin, are typical examples. Such lakes are salty because they have no outlets, and the principal, if not the only disposal of water, is through evaporation. Under such conditions the density of the solution varies with the water stage, the greater concentration occurring when the stage is low. A high stage promotes greater volume of evaporation because of the larger area and also because evaporation occurs in an inverse ratio to the density of the solution.

The effect of sodium chloride in solution was determined at the Fullerton Station using concentrations ranging from five to 25 per cent, comparison being made with fresh water. The test continued from June through December. It is summarized in Table 3.

The test with the 25-per cent solution was not conclusive, as the density was so near saturation that salt crystals formed on the inside of the pan above the water surface, were carried by capillarity up to the rim and down on the outside, where some of them were deposited on the surface of the soil. The average rate of decrease in evaporation from sodium chloride solutions is very nearly one per cent for each per cent of salt in the water.

Table 3--Summary of results of tests made with various concentrations of sodium chloride

Per cent of salt by weight	Relative evaporation
	pct
Fresh water ...	100.0
5	93.1
10	90.1
15	85.0
20	81.1

Evaporation from covered reservoirs--Small reservoirs covered by a protecting roof and ventilated by narrow screen openings are often used for storage and regulation of irrigation and domestic water supplies. Air conditions within a covered reservoir differ from those at open water surfaces. Water temperatures are fairly uniform, showing little effect of the changing daily air temperatures outside. Light is admitted only through the ventilating screen, which is small compared with the area of the water surface. No wind enters the reservoir, although a slow circulation of air occurs over the water as a result of convection currents. Consequently, evaporation is low and varies little from month to month.

Lowest evaporation from a floating Weather Bureau pan occurred when water was cooler than air, a condition that prevailed during the warmer months. The minimum monthly loss, occurring in August, was but 0.90 inch in contrast with 8.27 inches of evaporation from a similar pan outside the reservoir. When water in the reservoir was warmer than air, evaporation increased, reaching a maximum of 2.50 inches in November. At this time evaporation from the floating pan slightly exceeded that from a similar land pan, this relation continuing until March, when air again became warmer than water. Some conservation of water is effected by the reservoir cover, but not in sufficient quantity, if its value be capitalized, to pay for the cost of roofing. The principal benefit lies in preserving the purity of the water.

Evaporation studies at lakes and reservoirs--Lake Elsinore, covering about 5500 acres in Riverside County, presents an excellent opportunity for an evaporation laboratory. Water is supplied by the San Jacinto River, which flows only during winter and spring, and there has been no outflow since 1916. All the evidence indicates a tight lake bottom that prevents seepage losses of any consequence. Evaporation studies were undertaken at the Lake for the purpose of checking some of the Fullerton coefficients.

Evaporation was measured from both Weather Bureau and screened pans and was computed for the Lake by inflow, rainfall on the surface, and changes in levels. A considerable degree of accuracy was possible in arriving at evaporation through the long, dry summer months, when the only change in levels was through evaporation. During the three-year test average annual coefficients for both pans were identical with those found at the Fullerton Station, but prominent differences occurred in monthly coefficients (see Table 4). At Lake Elsinore maximum depth of water was about 40 feet, although large areas did not exceed ten feet as compared with a depth of three feet in the 12-foot pan; and differences in time and amount of heat storage should be expected.

Because of the small volume of water in evaporation pans, heat storage, available for the process of evaporation, varies hourly during the day, and much of the heat gained in the daytime is lost at night. Temperatures of large volumes of water are more uniform, they change but little daily and their seasonal changes are slow. A portion of the heat received by lakes and reservoirs in spring and early summer is used in evaporating the surface water, and another portion is absorbed in warming the water to a considerable depth. Later on, heat stored at depth returns to the surface and becomes available for evaporation during the cooler months when pan evaporation is approaching a minimum. During the earlier part of the season pan evaporation exceeds lake evaporation, but in the fall and early winter evaporation from the larger body of water may equal or exceed pan evaporation. Thus it may be expected that actual monthly evaporation from a reservoir will differ from computed values based on predetermined monthly coefficients. However, the annual heat energy received at lake and the pan should be the same, hence, annual reservoir evaporation should be nearly identical with that computed by means of annual coefficients.

The 12-foot pan, Rohwer's 85-foot diameter reservoir, and Lake Elsinore were regular in shape and without major obstructions to wind over the water surface. Many lakes and some reservoirs are of this type, but deep, narrow reservoirs in mountain canyons often have such irregular shore lines that water surfaces in bay areas are protected from winds where other areas are fully exposed. This condition exists at Morris Reservoir, in San Gabriel Canyon near Pasadena.

Studies in cooperation with the Pasadena Water Department were made over a six-month period to determine the effect of such irregularities on air and water temperature, humidity, wind, and evaporation in four selected locations on the reservoir surface and at the regular evaporation station on shore. Floats with recording equipment were anchored in two bay areas on opposite sides of the reservoir, one protected from wind upstream, the other from wind downstream. A third float was offshore several hundred feet above the dam, and the fourth was in midchannel where it was exposed to both up and downstream winds. The land station was on the western shore and at low water was considerably above the reservoir surface. Measurements were made daily, July through December, 1939, this period representing both summer and winter weather conditions.

Humidity was greater at the reservoir surface than at the higher land station and was nearly uniform at the different floats regardless of wind effect. Likewise there was little difference in mean air temperatures at any places of record. Surface water temperatures in the reservoir varied seasonally, but daily charts showed increases of one or two degrees only during short periods in the middle of the day. Water temperatures were the same regardless of the location or exposure of the float.

Table 4--Mean monthly evaporation and reduction coefficients for Southern California

Month	Fullerton, California 1936-39, inclusive					Lake Elsinore, California 1939-41, inclusive				
	Evaporation			Coefficients		Evaporation			Coefficients	
	12-foot pan[a] (sunken)	Screened pan (sunken)	Weather Bureau pan	Screened pan[b]	Weather Bureau pan	Lake Elsinore	Screened pan (sunken)	Weather Bureau pan	Screened pan	Weather Bureau pan
	in	in	in	ratio	ratio	in	in	in	ratio	ratio
Jan.	1.82	2.11	2.80	0.83	0.65	1.96	2.05	2.38	0.96	0.82
Feb.	2.20	2.34	3.06	0.93	0.77	2.00	2.59	3.15	0.77	0.63
March	3.30	3.12	4.35	1.06	0.76	3.24	3.53	4.78	0.92	0.68
April	4.44	4.30	5.58	1.03	0.80	4.20	4.82	6.34	0.87	0.66
May	5.81	5.73	7.21	1.02	0.81	5.92	6.54	8.72	0.90	0.68
June	6.74	6.62	8.26	1.02	0.82	7.04	7.15	9.15	0.99	0.77
July	7.41	7.35	9.14	1.01	0.81	7.96	8.36	10.74	0.95	0.74
Aug.	7.00	7.07	8.67	0.99	0.81	7.44	7.31	9.60	1.02	0.78
Sept.	5.85	6.12	7.67	0.96	0.76	6.32	5.72	7.27	1.10	0.87
Oct.	4.05	4.47	5.38	0.91	0.75	4.96	4.42	5.31	1.12	0.93
Nov.	3.09	3.59	4.30	0.86	0.72	3.16	2.83	3.25	1.12	0.97
Dec.	1.81	2.08	2.73	0.87	0.66	2.04	1.98	2.14	1.03	0.95
Year	53.52	54.90	69.16	0.975	0.77	56.24	57.30	72.83	0.98	0.77

[a] The 12-foot diameter pan is three feet deep, set 2.75 feet in the ground.

[b] The screened pan is two feet in diameter by three feet deep, set 2.75 feet in the ground and covered with 1/4-inch mesh wire hardware cloth. Screened pan records for six pan years are averaged in the Fullerton records.

Water in the reservoir often was warmer than air at the water surface, this condition occurring mostly at night, although continuous periods of 18 to 48 hours were noted, the differences being as much as 20 degrees. In only five out of 180 days was air warmer than water throughout the entire day, and water was warmer than air more than 60 per cent of the time.

Unlike temperature and humidity, wind varied greatly, being greatest in midchannel and least in bay areas. It exceeded wind at the land station by 200 to 340 per cent, showing the need for location of land evaporation stations in areas that are truly representative of reservoir surfaces. Often it is not possible to meet this condition because of difficult topography, and sometimes pans are not suitably located because such location would be inconvenient for the observer.

Evaporation from small pans on floats varied considerably, being least in sheltered areas and most in areas exposed to the greatest wind. Assuming evaporation from a similar pan at the land station as 100 per cent, the evaporation at the floats varied from 95 to 128 per cent, the greatest difference being in the exposed central portion and the least in bay areas.

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A DETERMINATION OF THE EFFECT OF TOPOGRAPHY UPON PRECIPITATION

William C. Spreen

Abstract--This paper describes a graphical correlation technique for relating mean winter precipitation in western Colorado to the topographic parameters; elevation, maximum slope of the land, exposure, and orientation. This is done by obtaining graphically values of precipitation as a function of elevation for various values of slope. Relating these values with orientation and thence exposure, a set of working charts is obtained. A high degree of correlation is shown to exist between the observed values of precipitation and those estimated from the charts.

The problem of constructing isohyetal maps of mean winter precipitation for the various drainage basins in western Colorado is, for the most part, a problem of estimating the effect of topography upon precipitation. The number of precipitation-observation stations in this particular area is comparatively small; therefore a rational approach to areal distribution of precipitation is desired.

In western Colorado, the winter precipitation is mainly orographically distributed and necessitates consideration of parameters other than elevation in any method used to estimate the distribution of precipitation. W. T. Wilson encountered this problem in his studies of precipitation in northeastern Wyoming. After extensive experimentation with many parameters, he found that the most applicable factors were: (1) Elevation of the station; (2) maximum slope of the land; (3) exposure of the station to the inflow of air masses; and (4) orientation of this exposure.

The definition of these parameters as used in this study is essentially the same as defined by Wilson. The parameters are: Elevation, station elevation expressed in thousands of feet; slope, maximum range in elevation within a five-mile radius of the station--expressed in whole thousands of feet; exposure, the sum of those sectors of a 20-mile radius circle, centered at the station, not containing a barrier 1000 feet or more above the station elevation. This is expressed in degrees of azimuth; and orientation, direction (to eight points of the compass) of the greatest exposure which is defined above. In cases of equal exposure in two directions, the orientation will be taken as that of the exposure which opens downstream, that is, toward lower elevation.

In his studies of exposure Wilson found a 20-mile radius to give the best results. However, it was felt that a smaller radius might be a better expression of station environment. A test was made using smaller radii, but the results indicated that a 20-mile radius was preferable.

Observational material--The data used were the mean three-month (December, January, February) winter precipitation values for the 11-year period 1920-30. The means were computed from the published values of precipitation in the United States Weather Bureau Bulletin W, and were limited to those stations in western Colorado with an unbroken record during that period. The topographic parameters, other than elevation, were obtained from United States Coast and Geodetic Survey Sectional Aeronautical Charts, scale 1:500,000.

The locations of the stations used in this study are shown in Figure 1. Table 1 lists the stations, precipitation amounts, and topographic parameters. In the Table, zero degrees for exposure and zero for orientation were used to indicate stations completely enclosed by a barrier within the 20-mile radius. The Table also shows the estimated precipitation derived from the graphical correlation and its departure from the observed amounts.

Explanation of the graphical correlation technique--Assuming that the effect of any one parameter upon precipitation was not independent of the other parameters, a method of graphical correlation was needed that would allow for such joint correlation among the independent variables. Such a method had been developed by Max A. Kohler [see "References" at end of paper, KOHLER, 1944] in connection with hydrologic studies.

The first step in deriving this five-variable correlation was to develop a family of curves relating three of the variables; precipitation, elevation, and slope. Precipitation was plotted against elevation and the points labeled with the corresponding values of slope. A first approximation curve was then sketched in for selected values of slope (see Fig. 2a).

A vertical axis was then drawn below the three-variable chart and was graduated for plotting actual precipitation. The axis common to both charts now represents the precipitation values as computed from the first family of curves. These values of computed precipitation were then plotted against actual precipitation values on the second chart, and the points labeled with the corresponding values of the fourth variable, orientation. A first approximation family of orientation curves was drawn (see Fig. 2b).

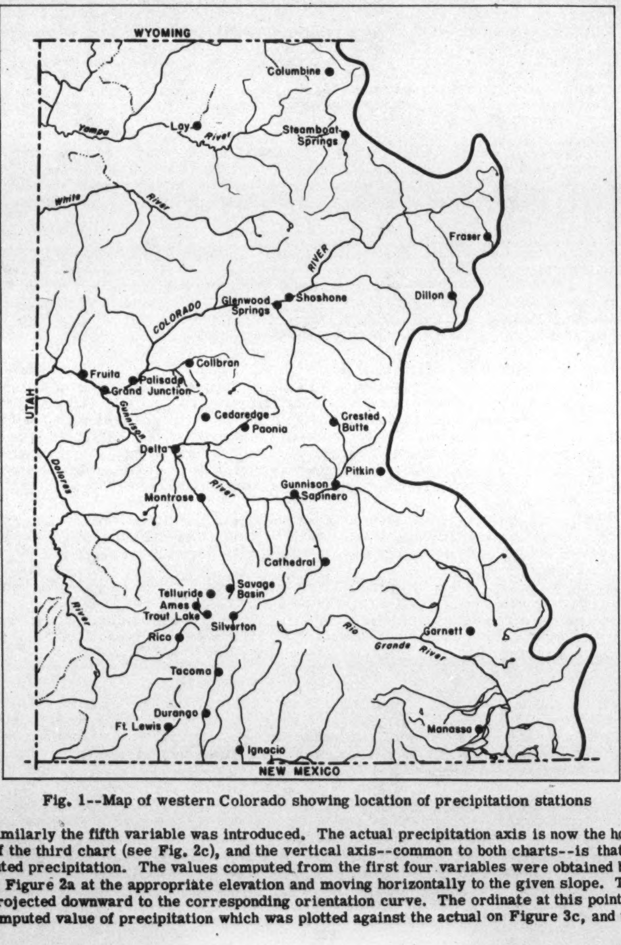
WYOMING
Columbine
Lay
Yampa
River
Steamboat Springs
White
River
Fraser
RIVER
Dillon
COLORADO
Glenwood Springs
Shoshone
Collbran
Fruita
Palisade
Grand Junction
Gunnison
UTAH
Cedaredge
Paonia
Crested Butte
Delta
Pitkin
Gunnison
Sapinero
Dolores
River
Montrose
Cathedral
Telluride
Savage Basin
Ames
Trout Lake
Silverton
River
Rico
Rio
Grande
River
Garnett
Tacoma
Durango
Ft. Lewis
Manassa
Ignacio
NEW MEXICO

Fig. 1--Map of western Colorado showing location of precipitation stations

Similarly the fifth variable was introduced. The actual precipitation axis is now the horizontal axis of the third chart (see Fig. 2c), and the vertical axis--common to both charts--is that of computed precipitation. The values computed from the first four variables were obtained by entering Figure 2a at the appropriate elevation and moving horizontally to the given slope. This point was projected downward to the corresponding orientation curve. The ordinate at this point was the computed value of precipitation which was plotted against the actual on Figure 3c, and the point labeled with the corresponding exposure value. The curves representing selected ranges of exposure were then drawn. Different groupings of the exposure angle were tried, but those indicated on the chart in Figure 2 fitted the data best.

Table 1--Topographic parameters and comparative values of mean winter precipitation in western Colorado, 1920-30

Station		Topographic parameters				Mean winter precipitation	Estimated precipitation	Error
Name	County	Elevation	Slope	Orientation	Exposure			
		1000 ft	1000 ft/5 mi		°	in	in	in
Collbran	Mesa	6.20	2	West	40	3.39	3.1	0.3
Dillon	Summit	8.90	3	North	10	3.79	3.2	0.6
Fraser	Grand	8.57	1	Northwest	60	5.04	5.3	- 0.3
Glenwood Springs	Garfield	5.82	4	0[a]	0	3.83	3.1	0.7
Grand Junction	Mesa	4.67	0	Northwest	80	2.06	1.2	0.9
Palisade	Mesa	4.74	1	West	65	1.36	1.9	- 0.5
Shoshone	Garfield	5.92	4	West	10	3.44	3.8	- 0.4
Cathedral	Hinsdale	8.92	2	North	25	1.31	1.6	- 0.3
Cedaredge	Delta	6.18	1	Southwest	100	2.13	2.9	- 0.8
Crested Butte	Gunnison	8.95	3	0[a]	0	5.71	4.8	0.9
Delta	Delta	5.12	0	West	55	1.46	2.2	- 0.7
Gunnison	Gunnison	7.68	0	Southwest	45	2.12	2.4	- 0.3
Montrose	Montrose	5.83	0	Northwest	90	1.40	1.4	0.0
Paonia	Delta	6.18	5	Northwest	40	4.11	4.0	0.1
Pitkin	Gunnison	9.18	3	Southwest	20	3.56	3.2	0.4
Sapinero (n)	Gunnison	9.35	1	West	210	6.02	5.9	0.1
Savage Basin	San Miguel	11.52	3	0[a]	0	8.89	8.8	0.1
Ames	San Miguel	8.75	5	Northwest	10	5.04	5.2	- 0.2
Columbine	Routt	8.77	1	Southwest	200	5.19	4.6	0.6
Ft. Lewis	La Plata	7.61	0	South	280	3.65	3.6	0.0
Fruita	Mesa	4.52	1	Northwest	135	2.59	1.5	1.1
Garnett	Alamosa	7.58	0	East	300	0.40	0.4	0.0
Ignacio	La Plata	6.42	1	Southeast	45	3.17	2.2	1.0
Lay	Moffat	6.17	1	West	75	4.13	3.8	0.3
Manassa	Conejos	7.70	0	North	250	0.43	1.0	- 0.6
Rico	Dolores	8.82	4	Southwest	10	5.77	5.6	0.2
Silverton	San Juan	9.40	4	0[a]	0	4.62	5.7	- 1.1
Steamboat Springs	Routt	6.77	3	West	50	6.96	6.6	0.4
Tacoma	La Plata	7.20	4	South	10	5.14	5.6	- 0.5
Telluride	San Miguel	8.76	5	West	20	3.51	3.9	- 0.4
Trout Lake	San Miguel	9.70	3	North	15	5.13	4.1	1.0
Durango	La Plata	6.55	1	South	160	5.12	4.5	0.6

Squared standard deviation of precipitation $\sigma^2 = 3.77$

Squared standard error of estimate $S^2 = 0.45$

Multiple correlation coefficient $R = 0.94$

[a] Station is completely surrounded by barrier.

Since all the sets of curves obtained by the above procedure were first approximations, further refinements were necessary.

A closer approximation of the slope curves was obtained by proceeding through the charts in the reverse order in which they were derived. Chart 2c was entered with the actual values of observed precipitation and exposure. Each of these points was projected to the left to its proper orientation, and again vertically to the appropriate elevation. These readjusted points were then labeled with their actual slope values. After plotting and labeling all the points, the slope curves were then adjusted.

In a similar manner the orientation family of curves was adjusted. From Figure 2a the point obtained for the value of elevation and slope was projected downward to Figure 2b. From Figure 2c the point obtained for exposure and actual precipitation was projected to the left to Figure 2b. The intersection of these two projections was plotted and labeled with the proper orientation value. After plotting all such points, the orientation curves were adjusted.

For the fifth variable, exposure, new computed values of precipitation were obtained from the first four variables and plotted against the actual precipitation on Figure 2c, and the curves adjusted.

Further refinements were made for all parameters by repeating the above procedures until no further adjustments to the curves were indicated.

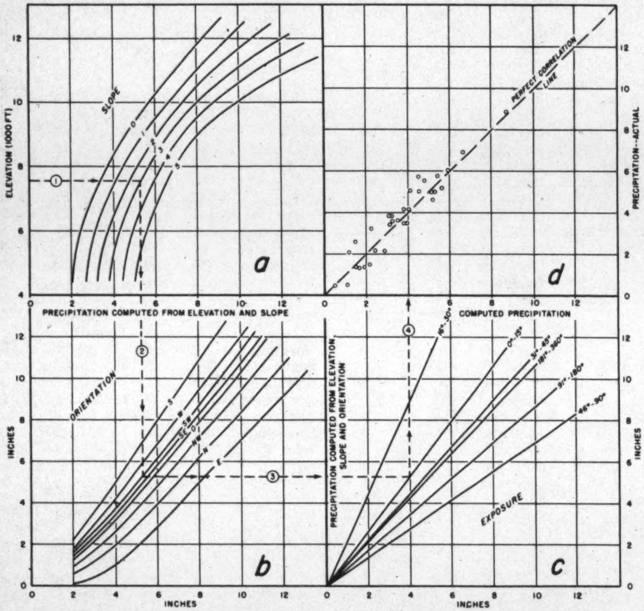

Fig. 2--Relation between precipitation and topographic parameters in western Colorado as obtained by graphic correlation for period 1920-30

To show graphically how the estimated values agree with the actual, the values obtained by proceeding through the adjusted charts (in the manner shown by the steps one through four indicated on the dashed line in Figure 2) were plotted against the actual values of precipitation (see Fig. 2d). The amount of scatter about the line of perfect correlation is shown on this chart. Both the horizontal and vertical distances from the 45-degree line are equal to the difference between the actual and estimated values of precipitation.

Figure 2 shows the relation of precipitation with the parameters used. The convergence within the various sets of curves indicates that there is a joint relationship among the parameters. If there were no joint relationship the curves would be parallel.

In the last two columns of Table 1 the estimated values of precipitation and the departures from the actual values are listed. A very close estimate was obtained in most of the cases. The squared standard error of estimate ($S^2 = 0.45$) was obtained by allowing eight degrees of freedom for the curves of the various parameters. The squared standard deviation of the actual precipitation, σ^2, was computed to be 3.77. From this the multiple correlation coefficient, R, was computed to be 0.94, indicating that about 88 per cent of the original variance was attributable to the four topographic parameters.

Many investigators have related the variation in precipitation solely to elevation by means of first, second, and third-degree equations [DONLEY and MITCHELL, 1939; LEE, 1911]. Others have subdivided the region under study into a number of sections on the basis of topography, direction of moisture travel, and location of principal mountain ranges, and have obtained a separate equation for each section [DONLEY and MITCHELL, 1939]. However, in the western Colorado region, when precipitation was plotted against elevation, the scatter of the plotted points indicated neither a sectional difference nor a curve greater than the first degree. A regression equation applied to the same data used in this study for precipitation, as related to elevation alone, was computed as $P = 0.62E - 0.88$. Precipitation, P, is expressed in inches and elevation, E, in thousands of feet. The correlation coefficient, r, was + 0.55, indicating that only 30 per cent of the variation in precipitation was attributable to elevation.

A comparison of the precipitation as computed by elevation alone and that computed by the four topographic parameters is shown in Figures 3 and 4. The computed precipitation values based on the four topographic parameters are by far more reliable than those based on elevation alone.

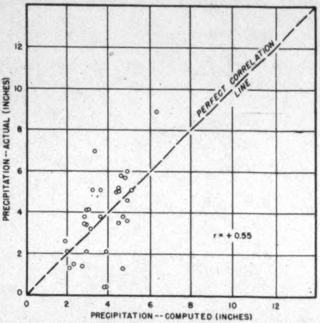

Fig. 3--Precipitation computed from elevation relation

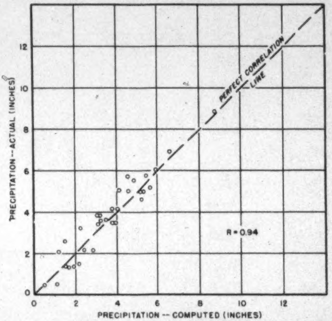

Fig. 4--Precipitation computed from elevation, slope, orientation, and exposure relations

Preliminary to this study, a larger number of stations were studied by means of the graphical correlation method as explained by EZEKIEL [1941]. The curves obtained for slope and orientation from the preliminary study were used as guides to drawing the first approximation curves in the later study. The effect of elevation and slope was similar in both studies, but there was marked difference between the results as reflecting the effect of orientation and exposure.

To test the graphically derived relations, the actual mean winter precipitation for the period 1916-20 for each of 26 stations was compared with the estimate of the mean precipitation based on the above relation between precipitation and the topographic parameters. A correlation coefficient of 0.87 resulted from the comparison of the actual and the estimated precipitation. This compares favorably with the original correlation coefficient of 0.94.

While the results obtained by this graphical correlation method appear to be very good, a comparatively small amount of data was used. It is hoped in the near future to adjust to a common time basis the mean precipitation of all the stations in western Colorado. This would permit the inclusion of many more stations in such a study and increase the confidence in the results. An attempt to obtain some relationship between precipitation and the topographic parameters through theoretical considerations is also in progress.

Acknowledgments--I wish to thank Ben H. Russler for his advice and guidance in this study, and Max A. Kohler for his advice and instruction in the use of the correlation technique.

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MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM APRIL 1, 1945, TO JUNE 30, 1946

Elliott B. Roberts

The close cooperation maintained in former years with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington was continued, by temporary loans of certain instruments and by exchange of data.

Magnetic surveys

In United States and Alaska--No repeat field observations were made. As usual, a number of observations of magnetic declination were made by parties of the Survey which were not engaged primarily in magnetic work. These included observations made at several airports in the United States, and in connection with hydrographic surveys along the coasts of the United States and Alaska.

In other American republics--The program of magnetic repeat observations in other American republics, which was begun in November 1941, continues. This work is being executed in cooperation with the Interdepartmental Committee on Scientific and Cultural Cooperation, United States Department of State. The fourth season's work, which began in February 1945, was concluded in June 1945. Observations in Peru, Chile, and Bolivia included observations of the daily variation.

The work of the fifth season, February to June 1946, included observations in all republics in the West Indies, all in Central America, and all bordering the Caribbean.

A special program of frequent repeat observations at the Parícutin Volcano, Mexico, begun in February 1945, was concluded in August 1945. The results have been published in the Transactions of the American Geophysical Union [see "References" at end of paper, KELLER, 1946].

The distribution of magnetic observations from April 1, 1945, to June 30, 1946, is shown in Table 1.

Work in the office

Furnishing data--As in previous years, magnetic data were furnished to nearly every agency of the Government which was engaged in making maps. The three-hour-range indices, K, were furnished daily to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, and to several Governmental agencies. Magnetic data were furnished daily to the National Bureau of Standards in connection with its program of forecasting radio transmission conditions.

A large number of inquiries were answered, providing specific data in most cases.

Work was completed on compiling data for a special research problem on the relation of quiet-day magnetic variations and meteorological changes. This project was proposed by Oliver R. Wulf of the United States Weather Bureau. The United States Coast and Geodetic Survey started on it in February 1943, under sponsorship of the United States Army Air Forces. After a few months of intensive work the project was dropped by that organization, and it was sponsored by the United States Weather Bureau until it was finished in July 1945. After the close of the War it was declassified, and the results have now been published [WULF, 1945].

Work on charts--The special project of furnishing isogonic data for regions scattered throughout the entire world for use of the armed forces was brought to a close.

Six more isogonic charts on a scale of 1:5,000,000 were issued. A total of 20 of the 43 originally planned were issued before the project was suspended. Over half of the Earth's surface is covered by those published. An index map of the published charts is available from the Director of the United States Coast and Geodetic Survey, Washington 25, D. C.

Table 1--Distribution of magnetic observations from April 1, 1945 to June 30, 1946

State or region	Repeat stations				Other stations	Totals
	New		Old			
	Complete	D only	Complete	D only		
Alabama	..	..	..	..	1	1
Colorado	..	..	..	..	1	1
Delaware	..	..	..	..	3	3
Georgia	..	..	..	..	1	1
Illinois	..	..	..	..	2	2
Indiana	..	..	..	..	1	1
Maine	..	..	..	..	1	1
Minnesota	..	..	..	..	1	1
Mississippi	..	..	..	..	1	1
New York	..	..	..	..	1	1
Oklahoma	..	..	..	..	1	1
Tennessee	..	1	..	..	1	2
Texas	..	..	..	..	3	3
Utah	..	..	..	..	1	1
Vermont	..	..	..	..	1	1
Virginia	..	..	..	..	4	4
Washington	..	..	..	..	1	1
West Virginia	..	..	..	..	1	1
Alaska	..	..	..	..	19	19
Canal Zone	1	..	..	..	..	1
Mexico	1	..	2	..	4	7
Costa Rica	..	..	1	..	..	1
El Salvador	..	..	1	..	..	1
Guatemala	..	..	1	..	..	1
Honduras	..	..	1	..	..	1
Nicaragua	1	..	..	..	..	1
Panama	..	..	1	..	..	1
Bolivia	2	..	1	..	..	3
British Guiana	1	..	..	..	..	1
Chile	3	..	..	..	..	3
Colombia	..	..	2	1	..	3
Peru	3	..	3	..	..	6
Venezuela	..	..	4	1	1	6
Antigua (Br.)	..	..	1	..	..	1
Bahamas	..	..	2	..	..	2
Cuba	1	..	3	..	..	4
Dominican Republic	..	..	1	..	..	1
Haiti	1	..	..	..	..	1
Jamaica	..	..	1	..	..	1
Trinidad	..	..	1	..	..	1
Totals	14	1	26	2	50	93

The isogonic chart of the United States for 1945 was issued. This edition of Chart 3077 marks a departure from former editions in several respects: It is prepared on a larger base map, showing more detail than formerly and extending farther into the North Atlantic Ocean; and the isogonic lines are drawn by a new procedure which more consistently reflects the local irregularity shown by the observations in different parts of the chart. Most of the work done in preparing this chart can be utilized without revision in the corresponding stage of preparing future isogonic charts of the United States. Work is in progress on the charts of other magnetic elements.

Work on publications--MD-8, "Alaska Magnetic Tables and Magnetic Charts for 1940," was issued during the year by offset lithography.

Serial 663, "Magnetism of the Earth," was issued during the year. It supersedes "The Earth's Magnetism," which was issued in 1925. Most of the material in the older publication has been carefully revised in the light of the latest information, and many portions have been considerably enlarged, especially the chapter on transient variations. The publication is for sale by the Government Printing Office.

Serial 664, "Magnetic Declination in the United States, 1945," was completed and sent to the Government Printing Office.

Serial 677, "Magnetic Observations in the American Republics, 1941-44," was completed, and at the end of the year the publication had reached the stage of second page proof. The volume will contain 95 pages, and will give a description of the project, the numerical results obtained, descriptions of the stations occupied, and a small isogonic chart.

The preparation of two volumes of results for observatories was completed during the year, for reproduction by offset lithography. These volumes were for San Juan 1929-30 and Honolulu 1937-38.

Miscellaneous--The personnel of the Section of Geomagnetism was considerably reduced after the War by voluntary separations, and the space occupied by the Section was reduced.

Observatories

The five magnetic observatories continued in operation without serious interruptions, and plans were made to build a sixth observatory.

Cheltenham, Maryland--Routine operation of three magnetographs continued. The scale values of the variometers are approximately as follows:

Magnetograph	D	H	Z
	′/mm	γ/mm	γ/mm
Eschenhagen . . .	1	2.7	4
Adie	1.1	4	12
La Cour.	4	30	--

The Adie instruments are equipped with eye-reading scales.

Field instruments of the United States Coast and Geodetic Survey and of other agencies were standardized at Cheltenham. The Department of Terrestrial Magnetism of the Carnegie Institution of Washington cooperated in maintaining the international magnetic standards.

College, Alaska--The United States Congress made an appropriation of $114,400 for the construction of a new magnetic observatory. It is expected that it will be built on the grounds of the University of Alaska, College, Alaska.

Honolulu, Territory of Hawaii--There are occasional mechanical disturbances in the vicinity of the observatory, because of the proximity of a landing field. Performance of the magnetograph was nevertheless reasonably satisfactory. A new observatory is under construction, and variometers and recorder to be used at the new installation were rebuilt.

San Juan, Puerto Rico--Routine operation of the magnetograph continued throughout the year.

Sitka, Alaska--Two magnetographs (sensitive and insensitive) were maintained in operation.

Tucson, Arizona--Normal operation of the magnetic observatory and cooperative work with the Department of Terrestrial Magnetism, Carnegie Institution of Washington, on atmospheric potential-gradient and positive and negative air-conductivity were continued. In May, 1946, an apparatus for recording ionization of the air was installed by G. R. Wait of the Department of Terrestrial Magnetism, for operation by the observatory staff.

Instrumental program

An automatic declination recording station was established at Gatlinburg, Tennessee, in latitude 35°41′.5 N, longitude 83°32′.0 W. The variometer is an ordinary Schultze declination-variometer, operated at a scale value of 1′.0/mm. The recorder is a modified electrocardiograph recorder, arranged to operate at a speed of two mm/hr and the recording tape is six cm wide. The recorder will operate several months without attention. To avoid blurring the record, the recording light is screened off most of the time, being allowed to reach the paper for only 30 seconds at the end of each five minutes. Although this station gives information about the daily variation, it is designed primarily to obtain accurate information on secular change at a cost comparable with that of obtaining much less accurate data by ordinary repeat observations. Operation began on September 3, 1945. Tapes were changed on September 18, 1945, and February 1, 1946. On April 5, 1946, the last tape was removed, and the instrument was dismantled for use as a model for additional instruments. It was put back into operation on July 21, 1946.

The new induction magnetometer [SWAINSON, 1945, p. 449; McNISH, 1946; GEBHARDT, 1946] was tested out on a field trip and found reasonably satisfactory.

Precision potentiometers, standard cells, and other electrical measuring instruments have been calibrated by the National Bureau of Standards.

A magnetometer and a dip circle with total-intensity attachment were prepared and standardized for use by Joel B. Campbell in connection with the Nanook project of the United States Navy. The route of this expedition is scheduled to cross the line joining the north geographic pole and the generally accepted position of the north magnetic pole. If observations (especially observations on land or on ice) can actually be obtained in that region, they will be a valuable addition to geomagnetic knowledge.

Assistance was given the War and Navy Departments in the instrumental aspects of various magnetic projects.

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REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

THOMSEN, HELGE, Isforholdene i de Arktiske Have (The state of ice in the Arctic seas, 1939), Danske Met. Inst., Kopenhagen, 1946.

The recent appearance of the 1939 issue of this unique publication marks the return after an absence of several years of the annual report of Arctic ice conditions. Five plates in color showing the mean monthly ice limits for April, May, June, July, and August follow 16 pages of text describing conditions in greater or lesser detail in different parts of the Arctic.

In the Greenland Sea the ice was considerably below the normal except in the estuaries of the fjords on the northeast coast. There the ice melted very slowly owing to the unusual combination of very heavy ice encrusted snow on the sea ice, and the absence of any gales during June and July which normally break up the ice at these points. The coasts of Iceland were free of ice throughout the year which is the sixth year in the 1930's with such unusually light ice conditions off Iceland. The light ice conditions in the Greenland Sea were associated with unusually severe ice conditions off Newfoundland and Labrador, another instance of a previously noted inverse relationship between ice in the Greenland Sea and ice off Newfoundland.

From the reports of the International Ice Patrol, the number of icebergs off Newfoundland south of latitude 48° N were 669 by actual count. The total is believed to be well over 800, because in May a considerable number of them drifted eastward with the ice pack before they could be counted.

There was also a considerable number of bergs in July; there were six in August. These late, very slow-drifting bergs were exceptionally large as indeed they had to be to appear so far south that late in the season at their slower rate of drift. The careful vigil by the International Ice Patrol was rewarded in an unusual way this season. For the first time it observed a large berg which broke up into three separate bergs and 22 good size growlers. The last berg observed in 1939 did not disintegrate until August 22 at 43°56'N, 44°18'. It owed its long life in these waters to its globular shape.

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Transactions, American Geophysical Union Volume 28, Number 2 April 1947

NOTES AND PERSONALIA

NOTES

Call for copies of "Hydrology"--The volume "Hydrology" of the Physics of the Earth series is now out of print, and a call is made for copies to be sent to European colleagues and libraries. The immediate need is for five copies, for which new price plus mailing charges will be paid for copies in first class condition. Persons having copies should get in touch with K. Hilding Beij (Secretary, Section Hydrology), National Bureau Standards, Washington 25, D. C.

Conference of Pennsylvania Geologists--The Annual Field Conference of the Pennsylvania Geologists will be held May 31 and June 1, 1947, at Lehigh University in Bethlehem. Field trips will cover the geology of the Lehigh Valley and study of the Paleozoic and Mesozoic formations. Correspondence regarding this should be sent to M. N. Shaffner, Pennsylvania Topographic and Geologic Survey, Harrisburg, or to Bradford Willard, Department of Geology, Lehigh University, Bethlehem.

National Science Foundation Legislation--Two bills relating to the establishment of a National Science Foundation has been introduced into the Senate as numbers S. 525 and 526. Copies of these can be obtained by writing to your congressman or senator. The text of the latter bill is published in Science, February 21, 1947, pp. 191-194, and the two bills are compared in Science, March 7, 1947, pp. 153-154.

Organization of Committee on Geophysical Sciences, Joint Research and Development Board--A Committee on Geophysical Sciences has recently been organized as follows: Roland F. Beers (Chairman), Carl G. Rossby, Chester R. Longwell, Samuel B. Morris, R. O. Glover, Howard B. Hutchinson, Benjamin G. Holzman, and D. N. Yates. R. H. Fleming has been designated as deputy for Admiral Glover, Daniel F. Rex for Captain Hutchinson, Moss Yater for Colonel Holzman, and W. S. Stone for Colonel Yates. C. S. Piggot is Executive Director of the Committee, and Helmut E. Landsberg is Deputy Director. The Committee was established to assist the Board in carrying out scientific research work in the geophysical sciences, including physics of the upper atmoshphere, meteorology of the lower atmosphere, geomagnetism, geology, hydrology, oceanography, seismology, and geodesy.

Pacific Science Board appointed--The Board appointed by the National Research Council in response to the recommendation of the Pacific Science Conference in the spring of 1946, includes Beno Gutenberg, Robert Cushman Murphy, Harald U. Sverdrup, and Remington Kellogg. Harold J. Coolidge has been designated as the Executive Secretary to the Board.

Resumption of thunderstorm research project--The thunderstrom research project, carried on by the Weather Bureau, Army, and Navy, under direction of Horace R. Byers of the University of Chicago, resumed field operations about April 1, 1947, with activities centered at Wilmington, Ohio. Work is continuing on the analysis of data collected in field operations last year at Orlando, Florida.

The Journal of Glaciology--The British Glaciological Society, founded in 1945, has begun the issuance of its new publication, The Journal of Glaciology, which will carry discussion of problems relating to various aspects of snow and ice. The Editor is Gerald Seligman, and the offices are located at the Royal Geographical Society, Kensington Gore, London, S. W. 7.

Earthquakes during January and February 1947--The region of the epicenter of the earthquake of April 1, 1946 which resulted in the strong tsunami of that date was visited by another shock on January 23 (see Table 1, 16_h U. T.). Reports from El Salvador after the earthquake of January 25 listed one person killed and some building damage in San Salvador. Damage was also reported from other places in the eastern sections of the country. The provisional epicenter determined by the United States Coast and Geodetic Survey (see Table 1) is near the mouth of Fonseca Bay between Nicaragua and El Salvador.

The earthquake of January 26, which was felt in eastern El Salvador, has been tentatively located by the Coast and Geodetic Survey in the mountainous sector of northwestern Nicaragua east of Fonseca Bay. Damage was reported at Puerto La Union, El Salvador on the northwest coast of the Bay. The shock was also felt at Managua, Nicaragua.

A light earthquake which shook the eastern and central parts of Honshu, Japan was reported from Tokyo on January 28 (3^h U. T. ?). Another deep-focus earthquake occurred on January 29, east of the Andes in Argentina in the vicinity of the epicenter of the earthquake of August 28, 1946.

C. F. Richter reports that Pasadena recorded an earthquake on February 5, which occurred in the California Coast Range (P wave arrival, $06^h15^m08^s$ U. T.). Information on the earthquakes listed in Table 1, have been secured by the United States Coast and Geodetic Survey cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismograph stations.

Table 1--Provisonal epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.		Epicenter				Remarks
			Lat.		Long.		
1947	h	m	°		°		
January 3	2	17.1	44	N	144	E	Off east coast Hokkaido Island, Japan
January 15	18	28.0	27	N	111	W	Gulf of California
January 21	20	06.7	25	S	70	W	Near coast of northern Chile
January 23	16	57.5	53	N	164	W	South of Unimak Island, Aleutian Islands
January 25	3	52.6	13	N	88	W	Fonseca Bay, between Nicaragua and El Salvador
January 26	10	06.7	13	N	86.5	W	Western Nicaragua
January 29	8	17.8	27	S	63	W	100 miles east of Santiago del Esterio, Argentina

PERSONALIA

H. Ahlmann, glaciologist, Chairman of the Geographical Department, University of Stockholm, has arrived in the United States. His schedule includes lectures at Johns Hopkins University of Chicago, University of California at Los Angeles, and in Cambridge, Massachusetts.

Tor Bergeron, Professor of Meteorology at the University of Uppsala, arrived in the United States in early April for a sojourn of several months. A portion of his time will be spent at the University of Chicago.

Marland P. Billings, Harvard University, has been elected Vice President of the Section of Geology and Geography of the American Association for the Advancement of Science, during 1947.

Detlev W. Bronk, Department of Biophysics, University of Pennsylvania, and Chairman of the National Research Council, has been elected to the Executive Committee of the Society of Sigma Xi for a five year term beginning June 30, 1946.

James E. Church, President of the Section of Hydrology, has gone to India on the invitation of the Indian Government to consult on the establishment of a snow survey system in the Himalayas. When Dr. Church left, it was his plan to fly to Chungking, thence over the "hump" to secure a view of the snow situation in China as well as in India. He plans to return by way of Khartoum, Dakar, and Rio de Janeiro.

Gordon M. Fair, Harvard University, has been elected Vice President of the Section of Engineering of the American Association for the Advancement of Science during 1947.

Robert F. Griggs, Department of Botony, George Washington University, and Chairman, Division of Biology and Agriculture National Research Council, has been elected to the Committee on Membership, Society of Sigma Xi for a five year term beginning June 30, 1947.

Ross Gunn, associated since 1927 with the Naval Research Laboratory, where he was Superintendent of the Physics Division, has joined the staff of the United States Weather Bureau as Director of Physical Research.

Bernhard Haurwitz, Professor of Dynamic Meteorology at Massachusetts Institute of Technology. has been designated as the Director of the Department of Meteorology of New York University.

I. Kaplan, Professor of Physics at the University of California at Los Angeles, is now Director of the University's Institute of Geophysics. At present, Professor Kaplan is working on studies of high-level atmospheric phenomena.

Gerhard Krumbach has been appointed Director of the Central Institute for Earthquake Research at Jena, Germany.

Walter D. Lambert, Chief of the Section of Gravity and Astronomy, Geodetic Survey, has been elected Correspondant of the Paris Academy of Science. Mr. Lambert retired April 1, 1947, after forty-one years of service with the Survey, and is now living at Lime Rock, Connecticut.

Kirtley F. Mather, Harvard University, has been elected to a four year term of the Executive Committee of the American Association for the Advancement of Science, beginning in 1947.

Martin A. Mason, Engineer with the Beach Erosion Board, has been named the recipient of the Washington Academy of Sciences Award in Engineering Science for 1946 "in recognition of his distinguished service in erosion studies leading to the successful invasion on Japanese (held) beaches--."

Clarence E. Palmer of New Zealand, well known for his work in tropical meteorology during the war, is to be a visiting scientist at the Institute of Geophysics, University of California at Los Angeles.

Irving I. Schell has established a laboratory for general meteorological research in Boston, and is continuing the study of Arctic ice as a factor in weather, monthly and seasonal variations in large scale circulation, and other problems.

Waldo L. Schmitt of the National Museum has been elected President of the Washington Academy of Sciences, Howard S. Rappleye has been elected Treasurer.

Robert P. Sharp of the University of Minnesota has been appointed Professor of Geomorphology at California Institute of Technology, effective September 1, 1947.

Byron T. Shaw has been appointed Assistant Administrator, Agricultural Research Administration, United States Department of Agriculture.

Lansing G. Simmons has been appointed to the position of Chief Mathematician in the Division of Geodesy to succeed the late Henry G. Avers.

H. W. Straley, III, consulting geological and geophysical engineer, has joined the staff of the International Bank to have charge of valuation of mining and oil properties.

F. J. M. Stratton, Secretary of the International Council of Scientific Unions, and Professor of Astrophysics at Cambridge University, England, will retire in October, 1947. Election of a successor as Professor of Astrophysics at Cambridge is now in progress.

Lorenz G. Straub of the University of Minnesota has gone to India on the invitation of the Indian Government to consult with regard to various features of the large, multiple-purpose dam now under design on the Godavari River, fifty miles above its mouth near Madras.

Merle A. Tuve, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been elected Vice President of the Section of Physics of the American Association for the Advancement of Science during 1947.

C. C. Wallen, University of Stockholm, is spending several months at the Institute of Meteorology, University of Chicago, on a fellowship of the Swedish-American Foundation. He delivered a lecture on "Glacial-meteorological studies and their relation to changes in climate and the general circulation" before a seminar group of the United States Weather Bureau in Washington, D. C., March 4, 1947.

Gordon R. Williams has left the United States Engineer Office in Boston to accept a position on the staff of the Knappen Engineering Company.

William A. Mattice of the Office of the United States Weather Bureau in Cincinnati, died October 19, 1946 at the age of 45. He was born in Catskill, New York and received his baccalaureate degree from George Washington University. Mr. Mattice devoted his entire professional career with the Weather Bureau, except for a brief period in 1936 and 1937, during which time he was with the Soil Conservation Service.

SPECIAL ANNOUCEMENTS

New England Meeting of the American Geophysical Union--Plans are under way for a New England Meeting of the American Geophysical Union to be held about mid-September, 1947. The General Committee for the meeting is being organized under the chairmanship of Richard M. Field of Princeton University and South Duxbury, Massachusetts. At the time of going to press, the Committee also includes: Charles F. Brooks, C. O'D. Iselin, H. B. Kinnison, Joe Webb Peoples, and Harlan T. Stetson.

Need for American Scientific literature in Vienna--A call is made by Volker Fritsch, Director, Department of Radio-Geology, Technische Hochschule, Gusshaus Strasse 25, Wien IV, Austria, for scientific literature from the United States and other Allied countries. He mentioned that he and his collaborators on research work are greatly handicapped by this shortage, and requests that books and reprints dealing with radio-geology and kindred problems be sent to him.

AMERICAN GEOPHYSICAL UNION

NATIONAL RESEARCH COUNCIL
OF
THE NATIONAL ACADEMY OF SCIENCES

Alphabetical List of Members of the American Geophysical Union, Officers of the Union and the Sections, and Committees of the Union

March 10, 1947

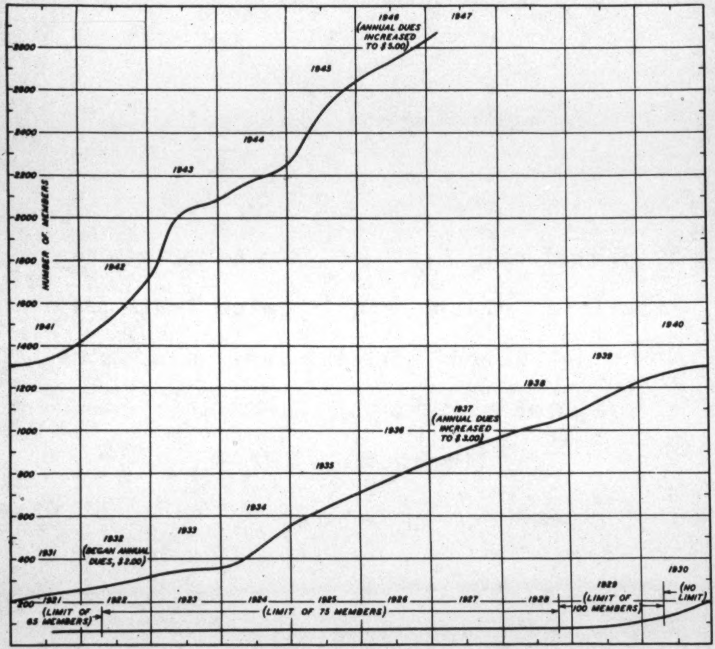
1530 P Street, N.W.
Washington 5, D. C.

PREFACE

Herewith is the first list of members published since October 1943. A list of the present officers of the Union and of the Sections and the members of Committees of the Union is appended. It is the plan to publish a geographical list of members and a list of the affiliations by Sections as soon as possible. With regard to the alphabetical list, the code letters following the names relate to the Section affiliations, as follows:

(a) Geodesy
(b) Seismology
(c) Meteorology
(d) Terrestrial Magnetism and Electricity
(e) Oceanography
(f) Volcanology
(g) Hydrology
(h) Tectonophysics

The numbers following the code letters are the last two digits of the year that membership began.



Membership, dates of increase in membership limit, and origin and increase of annual dues, American Geophysical Union, 1921-47

The total membership on March 10, 1947, was 2,880 including Members and Associates, 18 Life Members, four Ex-officio Members, and five Corresponding Members. This represents a growth of 805 Members since October 1943, showing that, despite the war years, there has been steady growth of interest in Geophysics and its applications.

AMERICAN GEOPHYSICAL UNION

ALPHABETICAL LIST OF MEMBERS
MARCH 10, 1947

Abbot, Dr. Charles G., Smithsonian Institution, Washington 25, D. C. (c) 20
Acheson, Mr. Volney A., Creole Petroleum Corp., Apartado 889, Caracas, Venezuela (abcdfh) 43
Ackermann, Mr. Casper J., 4935 Evans St., Omaha 4, Nebr. (acdg) 43
Ackermann, Mr. William C., Tennessee Valley Authority, Knoxville, Tenn. (cg) 38
Adams, Prof. Frank, 302 Giannini Hall, University of California, Berkeley 4, Calif. (g) 31 (Life Member)
Adams, Mr. Harry W., P. O. Box 868, Diablo Heights, Canal Zone (cg) 41
Adams, Mr. Henry P., U. S. Weather Bureau, Philadelphia, Pa. (cg) 46
Adams, Mr. John A., P. O. Box 524, Ogden, Utah (cg) 43
Adams, Dr. L. H., Geophysical Laboratory, 2801 Upton St., N.W., Washington 8, D. C. (bdfh) 20
Adams, Dr. Oscar S., R. F. D. 4, Mount Vernon, Ohio (a) 29 (Life Member)
Adams, Dr. Thomas C., 242 South 12th East St., Salt Lake City 2, Utah (abcg) 37
Adams, Dr. Walter S., Mount Wilson Observatory, 813 Santa Barbara St., Pasadena 4, Calif. (d) 30 (Life Member)
Adler, Dr. Joseph L., 901 Esperson Building, Houston 2, Texas (abdfh) 34
Affleck, Mr. James, Gulf Research and Development Co., P. O. Drawer 2038, Pittsburgh 30, Pa. (abdfh) 39
Aguerrevere, Dr. Pedro I., Venezuelan Embassy, 2445 Massachusetts Ave., Washington, D. C. (bdg) 41
Ahrens, Mr. Thomas P., 435 South Clay St., Denver 9, Colo. (cfgh) 40
Aikman, Dr. John M., Department of Botany, Iowa State College, Ames, Iowa (cg) 45
Akin, Mr. P. Donald, U. S. Geological Survey, University Station, Grand Forks, N. Dak. (g) 43
Albertson, Mr. Maurice L., Iowa Institute of Hydraulic Research, Iowa City, Iowa (cg) 42
Albritton, Dr. Claude C., Jr., 3436 University Blvd., Dallas 5, Texas (bfgh) 44
Aldredge, Mr. Robert F., Petroleos Mexicanos, Departmento Exploracion, Tampico, Mexico (b) 44
Aldrich, Dr. Henry R., Secretary, Geological Society of America, 419 West 117th St., New York 27, N. Y. (dfh) 35
Aldrich, Mr. L. B., Smithsonian Institution, Washington 25, D. C. (cd) 30
Aldrich, Mr. Ralph M., Weather Bureau Airport Sta., Kansas City 6, Mo. (cg) 46
Alexander, Dr. C. I., Magnolia Petroleum Co., P. O. Box 780, Tyler, Texas (abdh) 45
Alexander, Mr. Verne, Room 301, U. S. Court House, Kansas City, Mo. (g) 45
Alexander, Mr. Walter H., Jr., General Delivery, Livingston, Texas (cg) 42
Alin, Mr. Ake L., Consulting Engineer, 5927 N. 24th St., Omaha 11, Nebr. (abcefg) 34
Alkire, Mr. Herbert L., U. S. Weather Bureau, Baltimore 2, Md. (c) 46
Alkire, Mr. Robert L., 605 Union Building, Charleston, W. Va., (bc) 38
Allen, Miss Alice S., U. S. Geological Survey, Washington 25, D. C. (bdgh) 45
Allen, Mr. Charles Clarke, U. S. Weather Bureau, Pomona, Calif. (c) 46
Allen, Dr. Eugene T., 135 Pleasant St., Arlington 74, Mass. (f) 28
Allen, Mr. George C., U. S. Weather Bureau, Lambert Field, St. Louis 21, Mo. (cdeg) 46
Allen, Mr. Louis P., 4715 River Road, N.W., Washington 16, D. C. (cdeg) 46
Allen, Mr. Robert E., 141 West Parkwood Drive, Dayton 5, Ohio (bcg) 40
Allen, Mr. William H., Escola Tecnica de Aviacao, Rua Visconde de Parmaiba, 1316, Sao Paulo, Brazil (acdg) 45
Alley, Mr. Russell I., 106 S. Main St., Midvale, Utah (cg) 46
Alling, Prof. Harold L., Department of Geology, University of Rochester, Rochester 3, N. Y. (f) 34
Allis, Mr. John A., Soil Conservation Service, P. O. Box 741, Hastings, Nebr. (g) 36
Alpha, Mr. Andrew G., General Petroleum Corp., P. O. Box 1551, Great Falls, Mont. (g) 42
Alter, Dr. Dinsmore, Griffith Observatory, P. O. Box 9787, Los Feliz Sta., Los Angeles 27, Calif. (c) 30
Alter, Mr. J. Cecil, U. S. Weather Bureau, Cincinnati 2, Ohio (cg) 35
Althouse, Mr. Irvin H., P. O. Box 87, Porterville, Calif. (g) 41
Ames, Mr. Frank C., 2525 N.W. 28th St., Oklahoma City 7, Okla. (g) 43
Anderegg, Mr. Fred, Dept. of Geology, Princeton University, Princeton, N. J. (a) 47
Anderson, Dr. Alfred L., Dept. of Geology, Cornell University, Ithaca, N. Y. (cfh) 34
Anderson, Mr. Alvin G., 3625 22nd Ave. S., Minneapolis 7, Minn. (g) 37
Anderson, Dr. Charles A., U. S. Geological Survey, P. O. Box 633, Prescott, Ariz. (fh) 34
Anderson, Mr. Clarence A., R. R. 1, Box 57, Waco, Texas (cdg) 45

Anderson, Dr. Clifford N., 25 Chittenden Ave., New York, N. Y. (d) 30
Anderson, Mr. Clyde L., 4966 South State St., Salt Lake City 7, Utah (g) 43
Anderson, Mr. Fred S., U. S. Geological Survey, P. O. Box 696, Boulder City, Nev. (g) 43
Anderson, Mr. Henry W., 1539 Walnut St., Berkeley 7, Calif. (cg) 45
Anderson, Mr. Ivan E., U. S. Weather Bureau, Eureka, Calif. (cg) 46
Anderson, Dr. John A., P. O. Box 332, Pasadena 17, Calif. (b) 25
Anderson, Dr. Judson Lowell, Dept. of Geology, Johns Hopkins University, Baltimore 18, Md. (fh) 44
Anderson, Mr. Keith E., Geological Survey and Water Resources, Rolla, Mo. (fgh) 43
Anderson, Mr. Nils G., Apartment 2J, Shore Estates, Bath Ave., Long Branch, N. J. (c) 44
Anderson, Dr. Wilmer C., 4909 Hanford St., Douglaston, N. Y. (bd) 42
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TRANSACTIONS
AMERICAN GEOPHYSICAL UNION

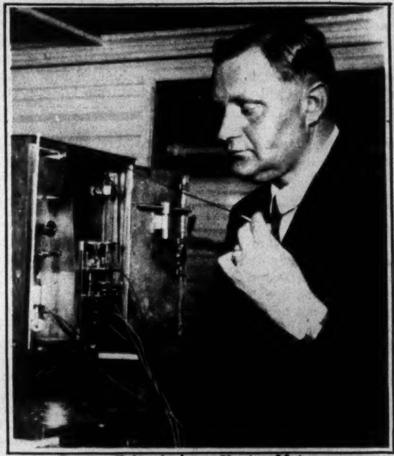
Volume 28 JUNE 1947 Number 3

CITATION

Frederick E. Wright

Mr. President: The Committee on the Award of the William Bowie Medal has requested me to give the reasons for the bestowal of the Medal this year to Felix Andries Vening Meinesz, Professor of Geodesy at the University of Utrecht in Holland, Director of the Royal Netherland Institute of Meteorology, Oceanography, and Geophysics at De Bilt, and Chairman of the Royal Netherland Geodetic Commission. For me to do this is a great honor and so great a pleasure that I shall consciously restrain myself in the use of laudatory adjectives.

The American Geophysical Union presents the William Bowie Medal to Felix Andries Vening Meinesz in recognition of his contributions to knowledge of the figure of the Earth through measurements of gravity on the ocean surface at various parts of the world and for his interpretation of the results thus obtained. For the purpose he perfected a method based on the use of a three-pendulum gravity apparatus aboard a submarine. With it he made satisfactory measurements of gravity at sea and thereby greatly extended the area of the Earth's surface over which gravity values can be obtained. In the course of his determinations of gravity, he discovered a belt of large negative anomalies near deep sea-troughs adjoining the convex sides of chains of islands in the East Indies, in the West Indies, and elsewhere. He interpreted these anomalies to be indicative of the presence of light surface materials down-warped and therefore of great importance in orogenic and tectonic theory.



Doctor Felix Andries Vening Meinesz
Recipient ninth award of William Bowie Medal
April 30, 1947
(Photo courtesy Underwood and Underwood)

In his Earth-wide tasks Doctor Vening Meinesz has cooperated heartily with scientists in many lands and is recognized as a creative and skillful geodesist and a profound student of Earth science. His colleagues respect him because of his good judgment and his genial, sterling character. To his students he is an inspiring teacher whose interests extend beyond his own field of research and who, by example, leads them along the path of the pioneer in quest of knowledge and truth and instills in them the spirit and enthusiasm of the creative worker in science. During the recent war he upheld the tradition of his country as a loyal citizen.

According to the deed of gift, the William Bowie Medal is awarded "for distinguished service in geophysics and for outstanding contribution to the advancement of cooperative research in this field of science." These qualifications aptly summarize the accomplishments and attainments of Doctor Vening Meinesz, and it is eminently fitting that the Medal be bestowed on him. We regret that he cannot be with us here to receive our personal congratulations.

It gives me special pleasure, Mr. President, on behalf of the Committee on Award, to recommend that the representative of the Government of the Netherlands receive the medal for Doctor Vening Meinesz and forward it to him through proper channels.

RESPONSE BY H. A. HELB

Counselor, The Netherlands Embassy

Mr. President, and Members of the American Geophysical Union: It is a great privilege for me to be present here tonight to accept on behalf of Professor Vening Meinesz, the William Bowie Medal which your learned and distinguished Union awarded him. I can assure you that I shall not fail to inform Professor Vening Meinesz about the proceedings of this evening and the words of appreciation which have been spoken here tonight.

Being myself an official of the Foreign Service of The Netherlands Government, you will, I am sure, forgive me that I personally do not venture into the fields, foreign to me, of your physics. But I can assure you that I am grateful that this evening has been another proof of the fact that international relations, and in particular those in the unselfish field of scientific research work, have been resumed after all these years of war and occupation, and that I am proud that a representative of the Netherlands has been able to uphold the tradition that during so many years the Netherlands have cherished.

On behalf of Professor Vening Meinesz I thank you for the honor which the American Geophysical Union has decided to confer upon him, and on behalf of myself I thank you for a delightful and instructive evening.

REPLY AND ACCEPTANCE BY PROFESSOR VENING MEINESZ

The news of the Award of the William Bowie Medal has given me so much pleasure that it is a privilege for me to write a few words about it. I need scarcely say that I deeply regret the impossibility to come in person to the United States for the ceremony; this would have given me the opportunity to address your meeting personally and to meet my friends who distinguish me by this great honor. I especially regret not being able to hear the kind words of my dear friend, Dr. Frederick E. Wright, to whom I feel bound by many ties among which those of a common souvenir of our submarine gravity expedition on board the U. S. Submarine S-21 to the West Indies.

For two reasons especially I appreciate the honor the Union bestows on me by awarding to me the William Bowie Medal. In the first place, it is because I think the American Geophysical Union is the most important national association in the field of Geophysics. It has quickly taken the first place among the different national groups of adepts of this new science and it is steadily developing its activities further. The Transactions of the Union have established an increasingly outstanding place. A distinction conferred by the American Geophysical Union has, therefore, special significance for the geophysicist.

In the second place, the Medal carries the name of an old friend of mine whom I held in high esteem for his selfless devotion to science. I owe him continuous support of my own scientific research which, for example, led to the two submarine expeditions to the West Indies where the U. S. Navy so generously offered me hospitality on board of their ships. This was indeed a unique gesture. My grateful remembrance of these expeditions involves what my friend, William Bowie, has done for bringing them about. I need hardly say that this makes the award of the Medal doubly precious to me. My work started on the geodetic side of gravity research, first on land, afterwards at sea. It gradually developed towards the physical and geological interpretation of the results and thus I feel myself closely related to the American Geophysical Union which shows so much interest in these subjects. I am sure I may accept the William Bowie Medal as a token of this interest and I feel deeply indebted to the Committee for singling me out for this great honor.

Transactions, American Geophysical Union Volume 28, Number 3 June 1947

THE GEOID STUDY OF THE INTERNATIONAL ISOSTATIC INSTITUTE

W. Heiskanen

Abstract--The author reports on the studies of the geoid made in the International Isostatic Institute during recent years. In order to be able to determine the undulations of the geoid we should know the gravity field over the Earth's entire surface, that is, the gravity anomalies. In the Isostatic Institute, Tanni has estimated the gravity field of the Earth as accurately as possible, taking into the consideration the isostatic reduction according to Hayford (T = 113.7 km). These anomalies with the aid of Stokes' formula give the undulations of the geoid.

The undulations of the geoid can be computed by two methods: With the aid of the deflections of the vertical, and with the aid of the gravity anomalies. The former method can be used only in those regions where triangulation nets with the necessary number of astronomical points have been determined. Such areas are rather small when compared with the Earth's total surface, and as the former method cannot be used at sea, the gravity method is much more practical.

In accordance with the resolution adopted by the International Association of Geodesy in September 1939, the Isostatic Institute has undertaken the computation of the undulations of the geoid by means of the gravity anomalies, making use of the Stokes formula. Because of the War this work has required more time than was estimated seven years ago.

The gravity-anomaly field must be known to a high degree of accuracy in the neighborhood of every point and to a less degree of accuracy over the whole Earth's surface if the undulations are to be well determined. Therefore, the first phase of the program was to collect all available gravity material and to study it critically. This was not easy. Too many gravity values are very inaccurate, especially the older observations, the errors of which, according to TANNI [see "References" at end of paper, 1942] can be 20 to 30 milligals and in some cases still more. Such measurements are, if the station net is not dense, totally worthless for the study of the geoid. It is difficult to decide which observations should be considered and which should be omitted. We of the Isostatic Institute have decided that all observations before 1890 should be omitted and that recent measurements, if such are available, should be used instead of the older ones.

A second difficulty concerns the national base stations, the accuracies of which vary greatly and in most cases are not too high. Hirvonen [HEISKANEN, 1941] has undertaken a new adjustment of approximately 100 national base stations, and he has found that some of these base stations need corrections of ten milligals or more. For instance, the correction to the Indian base station, Dehra Dun, is between + 10 and + 15 milligals. In the study of the geoid the newer base values have been used.

Thirdly, we have had difficulties with the topographic isostatic reduction of the gravity values. We have decided to use the isostatically-reduced anomalies. Because only a part of the gravity measurements have been reduced isostatically, we have been compelled to reduce, with a smaller accuracy, thousands of gravity stations, and this has taken much time. Table 1 lists the number of gravity stations for which isostatic reductions have been made available.

If we subtract from the total given in Table 1, the 1500 American stations, 844 sea stations, and 102 Japanese stations, there remain only about 2900 isostatically-reduced gravity stations for the old continent. Since the number of observed gravity stations is many times this figure, we must take into consideration in some way the material that has not been reduced isostatically.

L. Tanni, who has undertaken this study of the geoid, has proceeded in the following manner:

First, he compiled a card catalogue in which all stations of each square degree are written on the same card; if necessary he uses two or more cards for one square degree. This catalogue contains: (1) The state or the country, in order to help the orientation; (2) the name of the station, in order to avoid errors; (3) the coordinates of the station to the nearest whole minute or the nearest tenth of a minute; (4) the source of literature, because the results have been compiled from about 50 publications; (5) the year of observation, in order to estimate the accuracy of the measurements (the older measurements are less accurate, and the observations before the year 1890 have been totally omitted); (6) the base station, which is necessary for the correction due to the base-station value actually used (as already stated, there are about 100 base stations, some of which are poorly connected with each other); (7) the observed value of gravity g; (8) the elevation of the station or the depth of the sea beneath the station; (9) the density ρ beneath the station, if known (this is necessary because it has been used instead of 2.67 in the Bouguer correction); (10) the free-air anomaly $g_0 - \gamma_0$ calculated by the aid of the reduction formula $g_0 = g + 0.3086H$, where H is the height of the station in meters, and g in milligals; (11) the Bouguer anomaly $g_0'' - \gamma_0$, calculated by the aid of the formula $g_0'' = g_0 - 0.0419\rho H + (g' - g)$, where $(g' - g)$ is the "Gelände-reduction;" if the station has been reduced isostatically, a density of 2.67 has been used and the formula is $g_0'' = g_0 - 0.118H + (g' - g)$; and (12) the isostatic anomalies according to Hayford (the depth of compensation, 113.7 km); to Airy (the thickness of the Earth's crust, 60 km and 30 km), and at some stations anomalies based on other assumptions.

We believe this card catalogue gives all the data which are necessary for any study concerning the geoid. With the aid of this catalogue it is possible to estimate the accuracy of the mean anomaly value of any square degree.

Table 1--Gravity stations for which isostatic reductions have been made available

Continent	Country or region	Reference	Number
Africa	East Africa	BULLARD [1936]	134
Asia	Cyprus	MACE [1939]	13
	Ferghana	EROLA[a] [1941]	185
	India	SURVEY OF INDIA [1937, 1939]	506
	Indo China	Sala[a] (Manuscript)	260
	Japan and eastward	HEISKANEN[a] [1945]	102
Europe	Caucasus	HEISKANEN[a] [1924]	71
	Carpathian	TANNI[a] [1942]	310
	Eastern Alps	HOLOPAINEN[a] [1947]	300
	France and Algeria	Kajamaa[a] [HEISKANEN, 1939]	57
	Great Britain	Heiskanen[a] [Bullard and Jolly, 1939]	59
	Italy and western Mediterranean	Cassinis and others [HEISKANEN, 1939]	112
	Lithuania	Nuotio[a] [HEISKANEN, 1939]	15
	Norway	HEISKANEN[a] [1926]	46
	Soviet Union	GORSHKOFF [1936]	cir. 445
	Spain	SANS HUELIN [1926]	48
	Spitzbergen	BONSDORFF [1916]	11
	Switzerland	LEHNER [1930]	220
North America	Canada Mexico United States West Indies	HEISKANEN [1939]	cir. 1500
At sea	. . .	Vening Meinesz [photo-copy, 1947]	cir. 844
		Total	cir. 5300

[a] Isostatic reductions made by International Isostatic Institute.

New stations have been reduced isostatically by a shortened method. We estimate, by means of the topographic and bathymetric maps, the mean height of the neighboring zone A-J (considered as one zone), the mean height of the zones M and N, which are the most important in the isostatic reduction, and the mean height of the common zone 15-14. The heights of the intermediate zones are determined by linear interpolation. On the basis of these mean heights the common effect of several zones is computed by the aid of a nomogram. The correction due to the zones 13 to 1 can be taken from the world maps drawn in the Isostatic Institute.

This shortened method gives very good results on the level lands ($h<500$ m) and is nearly sufficient also for the mountainous regions or at sea, but only under the condition that the

Geländereduction (g′ - g) has been determined from good topographic maps of large scale (1:20,000; 1:50,000; or 1:100,000).

Therefore, it is very important that when publishing the results of their gravity measurements the various organizations give the Geländereduction (g′ - g) separately, in addition to the coordinates and heights of the stations and the observed gravity and gravity anomalies, as BORRAS [1911, 1914] has done. If we had the reduction (g′ - g) we would need only maps and charts of 1:1,000,000 and smaller scale for the topographic isostatic reduction, since the effect on the isostatic correction of the topography in the nearest Hayford zones is small.

If the stations are closely spaced we do not reduce them one by one, but we form an artificial station net, that is, with an interval of 1/4° or 1/2°, and draw the correction curves, from which it is easy to determine by interpolation the correction of the real stations. These curves are very regular, even in the high mountains, so that they are very useful in the practical reduction work.

As we now have new gravimeters in nearly every country at our disposal, we shall have in the near future a very dense gravity-station net. We may expect hundreds of thousands of new stations, so it will be quite impossible to reduce them all separately. It is much better to draw world maps giving the isostatic reduction of several Hayford zones. The Isostatic Institute has begun to prepare such world maps, which have proved to be very satisfactory.

There is another step forward. It is possible to get world maps which give the total isostatic reduction (from zone A to zone 1) from point to point. Such maps are very useful, at least for level land regions and for great parts of the oceans. I hope that the Isostatic Institute shall be able to publish such maps soon.

But which isostatic assumption is the best to recommend? It would be well to decide at the next congress of the International Association of Geodesy which isostatic system is best for world-wide geodetic and geophysical studies. In 1924 an International Ellipsoid, and in 1930 an International Gravity Formula were adopted. Why not adopt an International Isostatic System? According to many scientists the Airy floating system is nearer to the truth than the Pratt-Hayford theory. In addition to these there is the Vening Meinesz regional system, but since we do not know which regionality is the best, it seems to be wiser to consider only the local systems.

On behalf of the Isostatic Institute, I recommend the Airy system with the zero elevation corresponding to a thickness of 30 km of the Earth's crust and with a density difference of 0.6 between the sima and sial layers.

Tanni has used for the thickness a value D = 60 km, which in broad terms gives the same effect as the Hayford system with the depth of compensation, T = 113.7 km. The Hayford system has been used more than other systems by the geodesists. The reduction work shows that the value D = 60 km is too large for the Alps, for the Carpathians, and for the Mediterranean regions. If the value 30 km is taken as an International value, it will not be too difficult to convert from the system D = 60 or T = 113.2 km to the system D = 30 km.

The fact that the small thickness of the Earth's crust closely corresponds to the real conditions in the Earth's crust is advantageous in the isostatic reduction, since the mass of the Earth's crust and therefore the height of the geoid itself will change less when the assumed thickness of the Earth's crust is less.

In the computation of the geoid Tanni has, of course, used the well-known Stokes formula, which gives the undulations, N, of the geoid in the following way:

$$N = (1/4\pi)(R/g)\int S(\psi)\Delta g d\sigma \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where R is the Earth's mean radius, g the mean value of gravity, Δg the gravity anomaly, $d\sigma$ the surface element, ψ the angular distance of $d\sigma$ from the station, and $S(\psi)$ the Stokes function, which for the values $\psi = 38°57'43''.5$ and $\psi = 117°39'41''.5$ is zero, between these boundaries negative, and elsewhere positive. The largest positive values correspond to the values $\psi = 0° (+\infty)$ and $\psi = 180°$ (+ 3.08) and the largest negative value is at cir. $\psi = 71°$ (- 2.31). In order to determine N at some point we must integrate over the whole Earth's surface. We should know the gravity field, that is, the mean gravity anomalies everywhere in the world. This is not known at present. But with the aid of the now-known gravity field, N values can be determined which closely approximate the correct values.

The most difficult and time-consuming part of Tanni's work has been to compile the very heterogeneous gravity data from a period of over 50 years, to estimate its accuracy, to make the card catalogue, and to reduce isostatically more than 2000 stations. Having accomplished this it is easier to compute the mean anomalies of 1° × 1° and of 5° × 5°.

Here, also, a careful study is necessary. What is, in fact, the mean anomaly of one square degree? It can hardly be the arithmetical mean of the observed anomalies of this square degree. All of the stations could be in one corner of the square, or close to one another. Usually the gravity has been measured in the exceptional regions, perhaps near ore or oil deposits, where the anomalies may be very exceptional, perhaps 20 to 40 milligals either negative or positive. If we use the mean of these anomalies as the mean of the whole square, an error of about 20 to 40 milligals could exist.

Therefore, it is better to draw with the aid of all available gravity anomalies iso-anomaly curves which are partly hypothetical, and then, by means of these curves, to try to estimate the best mean anomaly of the square degrees. For this estimation it is good to know that the iso-anomaly curves usually follow the geological structure of the Earth's surface and often the topography as well.

In a few square degrees there are so many gravity measurements--in Europe only about 20 squares--that the mean anomaly can be determined with an accuracy of one milligal. In these squares there are ten to 300 stations. In most cases there are only one to 20 stations, and sometimes they are very unevenly distributed--such as all in a small area. For such cases the accuracy of the mean anomaly of a square degree can hardly be better than ± 5 milligals and in the case of the square degrees with only one station the accuracy is only ± 10 milligals.

For these reasons Tanni has given the mean anomalies of the square degrees with the accuracy of only ± 5 milligals--the last number of the anomaly is five or zero, and since the accuracy of the mean anomaly is not too high, it is not very important to reduce isostatically the stations with great accuracy. An accuracy of about ± 5 milligals is sufficient.

Since it is quite impossible to assume the mean anomalies of the square degrees where there are no gravity stations, we have used hypothetical anomalies in only a very few exceptional cases. On the gravity-field map Tanni has shown the figures in black for the squares where the anomalies are positive and in red where negative. The squares without any gravity measurements have been left blank. Using these maps, it would be very easy to compute the effect of such white squares afterwards, when gravity measurements are undertaken.

This gravity-field map indicates that the largest part of the Earth's surface is white--terra incognita. Therefore, new gravity measurements are of great importance, and it would be very fine if the big oil companies which have made some 100,000 gravity measurements in several parts of the world, would be kind enough to give a part of their results for scientific purposes. For the study of the geoid the mean gravity value of every square degree is sufficient and certainly would not interfere with the interests of a company. The geophysicists of some oil companies have already promised to send to the Isostatic Institute, Helsinki, such available scientific data. In addition to the oceans the white areas include Turkey, Arabia, Persia, Middle Asia, South America, Africa, and Australia.

With the aid of the 1° × 1°, map it is easy to prepare another map of 5° × 5° squares. In computing the general or universal part of the undulations of the geoid it seems to be better to use the squares 5° × 5°. The regional part we get easiest with the 1° × 1° squares and the local undulations with the 10′ × 10′ squares.

For the practical computation of the undulations of the geoid we need two maps on the same scale, one giving the value of the coefficient $c = (1/4\pi)(R/g)\int S(\psi)d\sigma$ in several squares, 1° × 1° or 5° × 5° in size, another giving the mean anomaly, Δg, of the square. Multiplying the corresponding values c and Δg and adding these amounts, we get the undulation, N, of the geoid at every such point on the Earth in the neighborhood of which gravity measurements have been made.

The accuracy obtained in this way corresponds to our present knowledge of the world's gravity field. Afterwards, when the white area of the anomaly map will be smaller, we can compute more and more accurate values of the undulations of the geoid. The undulations may rise to ± 100 m and at some places may be even higher.

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A NOTABLE FIGURE IN GEODESY

W. D. Lambert

The child later known to the world as General Georges Perrier was born October 28, 1872, at Montpellier, a university town in southern France, and christened Antoine François Jacques Justin Georges. He was the son of General François Perrier, internationally known for his work in geodesy, who reorganized the Service Géographique de l'Armée after the Franco-Prussian War.

The father died when young Georges was only sixteen, but by that time the lad had already decided to follow in his father's footsteps as far as possible. In 1892 he entered the École Polytechnique, which is no school for the dull or the lazy, and was graduated with distinction. The choice between a civil and a military career was open to him. He chose the army, and in particular the Artillery, but was soon assigned (1898) to the Geodetic Section of the Service Géographique de l'Armée.

He did geodetic work in France and North Africa and in 1901 was made a member of the French Mission to Ecuador and Peru to remeasure the old meridional arc originally measured by French Academicians in the eighteenth century to determine the figure of the Earth.

This was no holiday operation. Much of the work was done under conditions not very different from those with which the eighteenth-century mission had to contend. The weather was, of course, much the same, and it was a principal obstacle. At one station nearly 14,000 feet above sea level Lieutenant Perrier had to remain 92 days to complete his observations; at another lower-lying station two high peaks that he was set to observe were almost continuously hidden in the clouds. On only five occasions in 119 days were both peaks visible simultaneously. Perrier remained in South America five years and acquired an excellent knowledge of Spanish that was of great service to him in later life. After his return to France, late in 1906, he spent much time preparing for publication the observations obtained by the Mission.

Shortly after his return he married. Eight children were born of the marriage. He had the misfortune to lose two particularly promising sons, one as a child, the other as a young man about to enter on his career.

Perrier served on two boundary commissions before the outbreak of the First World War in 1914. He was captain at the beginning of the War, having acquired that rank in South America. Before the War ended he became major and lieutenant colonel. He was no mere headquarters officer, but saw service on various fronts, taking command on occasion and winning six military citations.

In 1919 he became Chief of the Section of Geodesy of the Service Géographique de l'Armée. Late in the same year the International Union of Geodesy and Geophysics was organized, and Perrier became Secretary of its Section of Geodesy. It is as Secretary of the Section (later renamed Association) of Geodesy that he was best known abroad. He held that office until his death. He held other positions also, military, and scientific. He was made Major General (Général de Division) in 1931, member of the Paris Academy of Sciences in 1926 and President in 1940, professor of geodesy and astronomy at the school of his youth, the École Polytechnique. Among his other honors may be mentioned membership in the Bureau des Longitudes, an organization having no exact counterpart in this country. As a soldier he wished to maintain the prestige of his country, but as a scientist and a man of international outlook he saw the necessity of cooperation among the nations, not only in science, where it is relatively easy, but in other fields where it is less easy.

Those who served with him or under him respected him for his knowledge, his zeal, and his devotion to his work. They liked him; "loved him" would not perhaps be too strong a phrase. But mingled with the love was not only respect but sometimes a little fear, due perhaps to his zeal for his work, a zeal to which not every one may attain. At the emergency meeting of the Executive Committee of the International Union of Geodesy and Geophysics in December, 1945 he was obviously feeling the burden of age and illness and kept going only by sheer force of will. When the end came on February 16, 1946, his last thoughts and his last words were of his work that he could no longer do.

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SEISMIC MEASUREMENTS ON THE ROSS SHELF ICE--Part II

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Abstract--Part I of this paper was published in the April, 1947, issue of the Transactions, pages 162 to 170.

The principal questions upon which interest has centered are the origin of the shelf ice, the natural causes which have maintained it almost unchanged over the years, the causes and directions of its movement, and the causes for the persistence of the various breaks along the Barrier and of deeply crevassed areas at various points over the sheet.

As a result of the scientific work of the Byrd Antarctic Expedition II from 1933 to 1935, information on most of these points is now available for about five thousand square miles of the Ross Shelf Ice. Using the geophysical equipment described in the first part of this paper, the author and his associates took soundings over an area extending from the Barrier south to latitude 80°07′ and in an east-west direction from Kainan Bay to Discovery Inlet.

Attempts to measure the rate of accretion of the shelf ice by snow gauges of various sorts must be regarded as unreliable. Widely as the records vary, it is quite apparent from the observations that the net accumulation on the surface of the ice in regions 100 miles or more from open water is only a small per cent of that occurring within 50 miles or less of open water.

The two most important processes whereby the density of the shelf ice is changed are: First, settling, either slow, or rapid through snow tremors; and, second, recrystallization. Although the density at the surface may be only one or two tenths, the average for the first five feet will be about five-tenths; but even at considerable depths the density is always appreciably less than that of solid ice.

A modified McComb-Romberg seismograph was used as a tilt meter, and a recurrent tilting of the ice was observed, having a period of about 25 hours and in the proper phase with the moon for a tidal effect. While it is impossible to determine the magnitude of the tide by this method, it is not unreasonable to suppose that a tide at least equal to that at Ross Island, namely, three feet, exists at the Bay of Whales.

Triangulations made in 1934 on some of the markers established in 1929, combined with accurate fixes from star sights of the position of Little America, provide the data from which the shift in position of the ice surrounding the Bay of Whales during this five-year period was determined.

The contour map presented in the preceding Part is now extended to several thousand square miles. Most of the seismic records show marked stratification of the bottom and two cross sections (Figs. 12 and 13) have been constructed. The cross sections of the Ross Shelf Ice, one across the Bay of Whales to Roosevelt Island, and the other south into the shelf ice east of Lindbergh Inlet, throw a great deal of light upon the condition of equilibrium that exists today.

A current of from one to three knots enters Okuma Bay and moves in a southwesterly direction, partly along and partly under the ice at Kainan Bay. It enters the Bay of Whales along the Barrier or emerges from under the shelf ice on the east side of the Bay, particularly through Eleanor Bolling Bight, crosses the Bay in a southwesterly direction, and again goes beneath the ice along the west side of the Bay. The current then travels west under the ice past or south of Lindbergh Inlet and out from under the ice in a northwesterly direction through Discovery Inlet.

The current underneath the ice where it projects out over the moraine causes a maximum amount of melting to occur along this path, thereby causing the major portion of the glacial material being carried by the shelf ice to be deposited on the forward edge of the moraine. This process is sufficient in itself to account for the origin of the Ross Shelf Ice.

The present seismic measurements of the Ross Shelf Ice have provided the first real information on its thickness, the thickness of the water layer under the floating portion, the contour of the bottom under the ice, the existence of large moraines, and the contour of the undisturbed rock surface below. It has been shown that a much larger proportion of the shelf ice is actually or practically in contact with the bottom than has hitherto been suspected. These data have provided the answers to many of our questions relative to the origin of the shelf ice and the persistence of its characteristic features.

Introduction--Ever since its discovery by Sir James Clark Ross, the Ross Shelf Ice has been the subject of speculation and controversy among students of the polar regions. As WRIGHT [see "References" at end of paper, 1925, p. 199] has said, "No single geographical feature of the Antarctic has, I think, excited so much general attention as the Ross Barrier." The principal questions upon which interest has centered are the origin of the sheet, the natural causes which have maintained it almost unchanged over the years, the causes and directions of its movement, and the causes for the persistence of the various breaks along the Barrier and of deeply crevassed areas at various points over the sheet.

Most of the speculations on these points have been of doubtful value because of the lack of certain vital information. Writers on the subject have been hampered particularly by want of data on the thickness of the sheet, its specific gravity, the directions and velocity of its movement, the extent to which it is grounded, the depth of the water under the parts which are afloat, the direction and velocity of currents under the ice, the rate of accretion of snow and frost on the surface, and the quantity rate of discharge of glaciers from the surrounding land masses.

As a result of the scientific work of the Byrd Antarctic Expedition II from 1933 to 1935, information on most of these points is now available for about 5000 square miles of the Ross Shelf Ice, over half the area included in the accompanying map (see Fig. 5). Using the geophysical equipment described in the first part of this paper, the author and his associates took soundings over an area extending from the Barrier south to latitude 80°07′ and in an east-west direction from Kainan Bay to Discovery Inlet. Data thus obtained on the thickness of the ice and the depth of the water under it, together with our accurate determinations of survey control stations by means of star sights and our observations of currents and tides, have provided the information necessary for determining the cause for the direction and rate of motion of the shelf ice, for the persistence of the Bay of Whales and other features of the Barrier, and for the position of many of the crevassed areas. As a result of the new information on the configuration and composition of the floor of the Ross Sea (see Table 2), we now have a tangible basis for hypotheses as to the origin and continuance of the shelf ice which combine with our other information to form a comprehensive and consistent picture.

Physical structure of the ice--There is no observation on record of any large percentage of solid ice or glacial drift in the Ross Barrier, and no glacial material has been observed in tipped or overturned bergs from that locality. Strictly speaking, the absence of glacial material has not been proved from positive evidence, for a berg sufficiently eroded to overturn may be presumed to have lost the load of glacial material originally on its under side. But on the basis of other facts known about the Ross Shelf Ice, it may be considered a practical certainty that the mass along the Barrier is composed almost entirely of firn, or névé. The firn which reaches the Barrier is generally agreed to have been formed upon a basement of glacial ice, which progressively disappears during the progress of the sheet across the Ross Sea. The glacial ice which descends from the surrounding highlands and crosses the natural borders of the sea already carries with it a load of fallen and drifted snow at the time when it begins to form a part of the ice sheet; but much the larger part of the snow-ice which finally reaches the Barrier has accumulated during the centuries of progress of the shelf ice to the Barrier face.

Many attempts have been made to measure the rate of accretion of the shelf ice by snow gauges of various sorts. Because of the wide variation and rapid changes in drifting conditions, all figures for weekly or monthly rates must be regarded as entirely unreliable. Even measurements of annual accumulations must be used with caution. The most dependable estimates are those based on differences of level observed over a period of several years. For example, Mackintosh, traveling with the party which discovered Scott's Depot A six and one-half years after its establishment, measured a rise in snow level amounting to 38 cm per year [WRIGHT and PRIESTLEY, 1922, p. 162]. It must be remembered that such figures obtained at one spot represent the rate of accretion at that spot only, and that the rate somewhere else on the shelf ice may be very different. WADE [1945, p. 168], quoting Mackintosh's estimate, observes that it is less than half of the annual accumulation measured at West Base. The values for West Base, however, were obtained from observations over a period of only 348 days and hence cannot be employed with any great assurance in computations of the accumulation over a long period of years.

Table 2--Seismic data from selected stations

Station	Distance from edge	Elevation	Sea level to bottom of ice	Thickness of ice	Floating above sea level	Thickness of water layer	Sea level to bottom of sea	Sea level to minor reflections	Sea level to lower reflecting horizon	Thickness of moraine
	mi	ft	ft	ft	pct	ft	ft	ft	ft	ft
89	13	140	534	674	20.8[a]	0	534	1575	2040	1506
90	23	140	354	494	28.3	226	580[b]	1690	2000	1420
91	2	100	753	853[b]	11.7	162	915	...	1885	970
100	0	2	13	15	...	1878	1891	...	2210	319
101	0	2	13	15	...	1687	1700	1935	1990	290
102	0.1	147	384	531[b]	27.9	1301	1685	...	2012	327
103	2	155	424	579	26.8	1313	1737	...	1990	253
104	2	160	594	754	21.2	974	1568	1855	1990	422
105	2	170	583	753	22.6	1032	1615	1900	1990	375
106	2	170	572	742	22.9	928	1500	1796	2052	552
107	0	3	27	30	...	1483	1510	1805	1990	480
108	0.2	140	664	804	17.4	843	1507	1770	1975	468
109	4	170	654	824	20.6	932	1586	1880	1950	364
110	4	170	719	889	18.9	883	1602	1880	2110	508
111	6	140	680	820	17.0	980	1660	...	1905	245
112	0.1	150	764	914	16.4	918	1682	...	1915	233
113	0.1	147	777	924[b]	15.9	846	1623	...	1910	287
114	0.2	117	733	850	13.8	872	1605	...	1910	305
115	0	3	27	30	...	1942	1969	1998	2265	296
116	0	3	27	30	...	1903	1930	2005	2266	336

[a] The ice is grounded at Station 89. [b] This value was given incorrectly in Table 1.

If direct measurement of the change in snow level is difficult, the measurement of precipitation is even more so. The air during an Antarctic blizzard is filled with flying snow, and apparently there is no good way of telling what part of that snow is actually being precipitated and what part has simply been picked up from one area, to be deposited eventually somewhere else. Consequently, all efforts to differentiate newly fallen from drifted snow have failed, and we are forced to fall back on estimates of the accumulation actually to be observed over an area large enough that snow temporarily blown away from one part may be assumed to be balanced by an equal amount temporarily received from another part.

Though it may be impossible to measure the amount of precipitation, it is necessary to recognize variations in the amount over the sheet. Widely as the records vary, for the reason just stated, it is quite apparent from the observations made by Byrd at Bolling Advance Weather Base [GRIMMINGER and HAINES, 1939, pp. 103-108] and by field parties traveling southward during the summer months that the net accumulation on the surface of the ice in regions 100 miles or more from open water is only a small per cent of that occurring within 50 miles or less of open water.

Not enough importance has been attached in the past to the part played by frost crystals forming on the surface of the shelf ice in the region along the Barrier. There is clear visual evidence of the fact that the winds blowing landward, carrying vapor at a temperature near the dew point, lose much of their moisture soon after crossing the edge of the shelf ice. Proof of this fact is to be seen in the heavy layers of frost frequently building up on the ice along the seaward edge, an effect which becomes decreasingly observable as one travels south from the Barrier. Although there is some gradual slope to seaward along the immediate edge of the shelf ice, this is only because the melting from beneath overbalances the accumulation of frost on top. As a result of this melting the ice settles along the edge. But southward from this narrow border the rapid formation of frost raises the surface to an elevation of 10 to 50 feet above the average level of the Barrier edge.

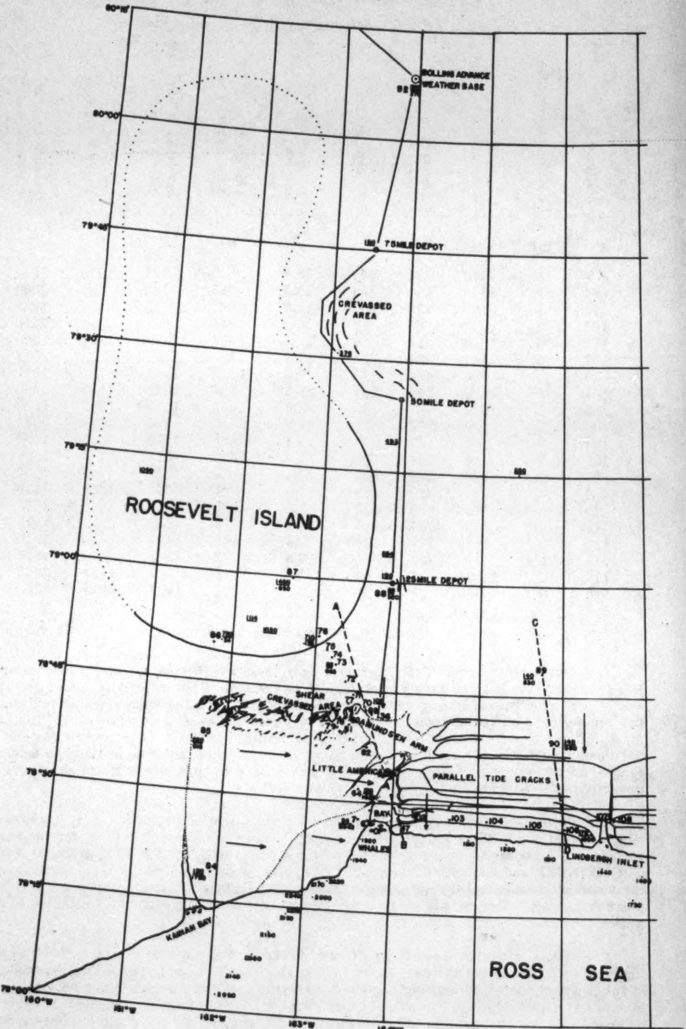
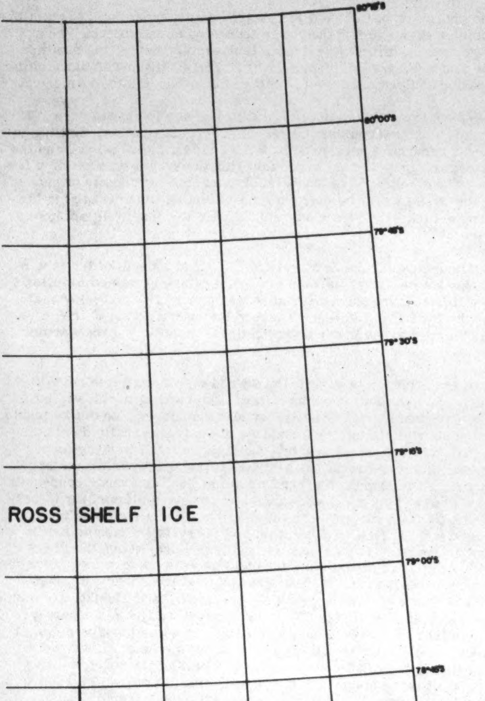

BOLLING ADVANCE WEATHER BASE
75 MILE DEPOT
CREVASSED AREA
50 MILE DEPOT
ROOSEVELT ISLAND
25 MILE DEPOT
A
C
SHEAR CREVASSED AREA
AMUNDSEN ARM
LITTLE AMERICA
PARALLEL TIDE CRACKS
BAY
WHALES
B
LINDBERGH INLET
KAINAN BAY
ROSS SEA
80°15'
80°00'
79°45'
79°30'
79°15'
79°00'
78°45'
78°30'
78°15'
78°00'
160°W
161°W
162°W
163°W
164°W
165°W
166°W
167°W

Figure 5--Bay of Whales section of Ross Shelf Ice showing location level, and distance from sea level to bottom, thus: 0.109 $\frac{170}{1586}$; the elevation of surface above sea level and 1586 is distance from sea ice movement


80°15'S
80°00'S
79°45'S
79°30'S
79°15'S
79°00'S
78°45'S
78°30'S
78°15'S
78°00'S
ROSS SHELF ICE
DISCOVERY INLET
109
110
111
113
115
116
210
168°W
169°W
170°W
171°W
172°W

of seismic stations, elevation of surface above sea dot locates the station, 109 is its number, 170 is level to bottom. The arrows indicate the direction of

Density of the shelf ice--The character of the shelf ice varies greatly from point to point even over short distances. It is the opinion of the author that, even though no actual melting occurs, the condition of the snow near open water is so affected by the air temperature during the summer months that observations made in that area are far from reliable. The shelf ice was more uniform vertically and free from stratification at Byrd's Advance Weather Base than at Little America.

The two most important processes whereby the density of the shelf ice is changed are : First, settling, either slow, or rapid through snow tremors; and second, recrystallization. Settling in the Ross Shelf Ice was perhaps most accurately measured by WADE [1945, pp. 162-166], and the stratification that he observed is probably due in part to the fact that the station was within a few miles of the edge of the shelf ice. The density of the lower levels increases gradually at such a rate that, although the density at the surface may be only one or two tenths, the average for the first five feet will be about five-tenths; but even at considerable depths the density is always appreciably less than that of solid ice.

WADE'S [1945, pp. 169-172] figures show fluctuations of only 15° F at a depth of ten feet and indicate that at any point 35 feet or more below the surface the temperature remained practically constant the year round. At 65 feet the year-round temperature was about -10° F. Below that level it rose gradually to slightly over -8° F at 135 feet. These values were obtained at West Base, near Eleanor Bolling Bight; the rise at the lower levels reflects the effect of the warmer water under the ice.

Snow tremors--The surface of the shelf ice is generally covered with a very fine snow usually compacted, but occasionally loose to a depth of as much as a foot. The hard, wind-blown, and eroded surface, in spite of its very low density, may be rigid enough scarcely to leave foot prints. The erosion by means of wind and surface drift and the formation of sastrugi usually do not disturb the snow to a depth of more than two feet, and below this depth a gradual transition is continually in progress. A small crystal of any material has a higher vapor pressure than a larger one of the same material, and as a result the smaller crystals sublime, and the vapor condenses on the larger ones, causing them to grow. This process is aided by the circulation of air to considerable depths, the extent of the circulation varying with the locality. The air circulation is in turn accentuated by an irregular sastrugi surface. Sublimation and recrystallization do not in themselves change the density; but as the crystal size increases, the physical strength of the structure decreases. If the humidity of the air circulating through the snow is very low, there may even be some temporary decrease in density, with a further weakening of the structure. Such a layer frequently becomes so unstable that it cannot support the overburden, and a relatively minor disturbance may cause a considerable area to collapse. The surface may settle only a barely perceptible amount, or it may fall an inch or more. Even the collapse of a comparatively small area will produce quite a loud report. This phenomenon, known as a snow tremor, is very disturbing to a dog team, particularly if they have had the experience of breaking through the thin bridge of a crevasse. A snow tremor of large magnitude may spread out for miles in all directions, with a loud rumble like distant thunder. Although a seismic wave from such a tremor travels at the normal velocity of 12,050 feet per second, the actual progression of the snow failure is very much slower.

Minor snow tremors started by sledging or skiing were very common, particularly following days of high wind velocity and relatively low temperatures. The larger snow tremors were usually initiated by the detonation of an explosive charge for obtaining seismic records. On one occasion such a tremor was audible for nearly 20 minutes and continued beyond another field party operating at a distance of more than 15 miles.

Circulation of air in ice--The fact that snow tremors are most frequent following a high wind that has persisted for several days is an indication of the influence of high wind velocities upon the circulation of air through the upper part of the shelf ice. On different occasions a two-inch hole was drilled to a depth of about six feet in the floor of some of the tunnels in the camp of Little America, and if a strong wind were blowing, so as to produce a suction on the tunnel system, an air current, up out of the hole, could be felt by holding the hand as much as two feet above the opening. The floors of the tunnels were ten feet below the general level of the snow surface. The temperature fluctuations down to 10 or 15 feet below the surface, paralleling the changes in air temperature although lower in magnitude, indicate a large subsurface circulation of air at this station. This movement of air through the surface snow accelerates sublimation and granulation, and the vertical components of air movement tend to remove any stratification which may have occurred in the snow structure.

Tide in the Bay of Whales--Attempts were made in 1934 to measure the tide in the Bay of Whales by inserting a tube through the bay ice and filling it with gasoline or some other liquid which would not freeze. A wire, attached to a heavy weight on the bottom of the Bay, was passed through the tube and connected to a tide meter mounted on the ice above the tube. This method, however, proved to be impractical, as the current, sometimes in excess of two knots, would produce a displacement of the 2000-foot long wire and therefore give a false indication of several times the actual magnitude of the tide and not in the proper phase with the moon. A qualitative method of detecting the presence of a tide was then substituted for the more direct method. This consisted of setting up a very sensitive tilt meter in a room hollowed out of the shelf ice at Little America. For this purpose a modified McComb-Romberg seismograph was used (see Fig. 6)

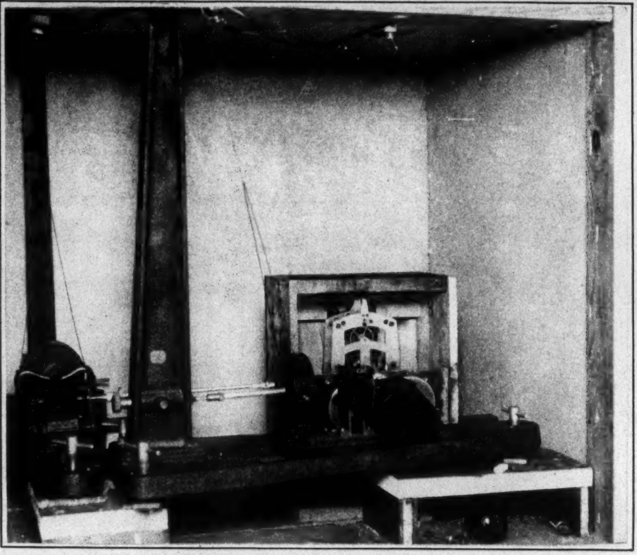


Figure 6--Modified McComb-Romberg seismographs used as tilt meters for detecting the presence of tides

As long as the crack which developed, completely surrounding Little America during March, 1934, remained active, the tilt meter showed a frequency of approximately four complete oscillations a minute, but as winter approached and the piece of ice on which the camp was built froze in more solidly with the surrounding ice, a recurrent tilting of the ice was observed, having a period of about 25 hours in the proper phase with the moon for a tidal effect, and giving the horizontal pendulum of the tilt meter an amplitude of a few inches. While it is impossible to determine the magnitude of the tide by this method, it is not unreasonable to suppose that a tide at least equal to that at Ross Island, namely three feet, exists at the Bay of Whales.

Water current--A current of about two knots enters Okuma Bay and flows southwestward along the face of the shelf ice past Kainan Bay. This current passes under the ice, some of it entering through Kainan Bay. This current enters the Bay of Whales from the northeast under the ice on the east side, particularly through Eleanor Bolling Bight. The current crosses the Bay of Whales in a southwesterly direction, and the major portion goes under the ice at the west side of the Bay, although there is a very limited low-velocity current flowing in a northwesterly direction along the west side of the Bay of Whales, which enters Chamberlain Harbor, Floyd Bennett Bay, and Sunnyside Inlet. A current of two to three knots sets northwest out of Discovery Inlet, and a westerly current of about three knots flows along the front of the Ross Ice Barrier all the way to McMurdo Sound and continues from there to the northwest. The velocity of the current varies with the tide, having a maximum at McMurdo Sound of about three knots and a minimum value of nearly zero.

The directions and velocities as just given have been verified by observations at various points and in different seasons. Measurements through holes in the bay ice during the winter night showed a current of from one to two knots to the southwest under the ice. A current of two knots flowing westward was observed in open cracks in the ice at Seismic Station no. 107, four miles from the Barrier edge in Lindbergh Inlet. An examination of the contour map (Fig. 7) will show that this current follows the low in the bottom from Kainan Bay across the Bay of Whales in a southwest direction, southwest under the ice and out under Discovery Inlet, where the low is rather narrow and sharply defined.

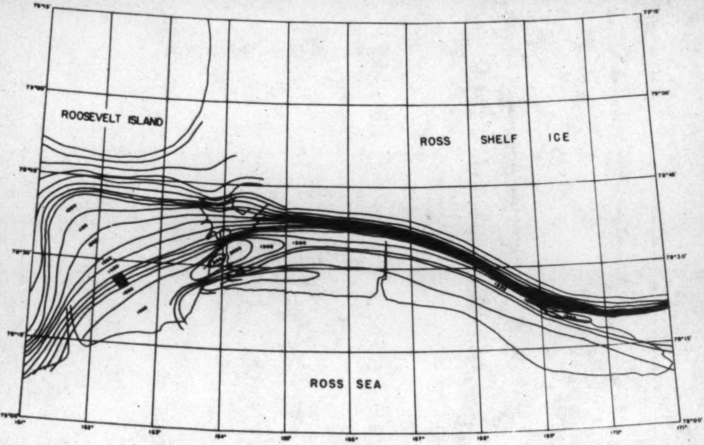


Figure 7--Contour of the bottom under the ice as determined from seismic measurements

Ice movement--Even casual observation of the enormous areas of pressure ice around the Bay of Whales is sufficient to make one realize that the ice movement is on a large scale, but actual measurements will prove surprising even to the trained glaciologist. Except in rather steep glaciers, one is apt to think of ice movement as being measured in fractions of a foot per day; but here on the Ross Shelf Ice, where the surface is essentially level, it is not uncommon for the forward edge of an ice sheet nearly 1000 feet in thickness to be advancing at the surprising rate of 12 or more feet per day. Triangulations made in 1934 during the Byrd Antarctic Expedition II on some of the markers established by Blackburn and Coman in 1929 on the Byrd Antarctic Expedition I, combined with accurate fixes from star sights of the position of Little America, provide the data from which the map (Fig. 8) was constructed showing the shift in position of the ice surrounding the Bay of Whales during this five-year period. To facilitate comparison, a map of the Bay of Whales for 1929 is superimposed on the map constructed in 1934.

The map shows that the ice on the west side of the bay is moving due north with a velocity of 6.6 feet per day, while that on the east side of the bay is moving slightly north of west with a velocity of seven to ten feet per day until it comes into contact with the northward-moving ice on the west side of the bay and eventually is carried out in a large piece, thereby forming a new Bay of Whales. Since the shelf ice south of Amundsen Arm has been shown by our seismic measurements to be grounded, it is probable that this region will most commonly form the southern boundary of any large new Bay of Whales.

As the Bay continues to close in, the relatively thin ice west of Cape Manhue is folded and crushed (see Fig. 9), with no appreciable decrease at first in the rate of advance of the ice. However, as this folded ice freezes into a thick mass, the thicker shelf ice bearing against it is slowed down. This is shown by the decrease in the rate of westward motion of the ice on the west

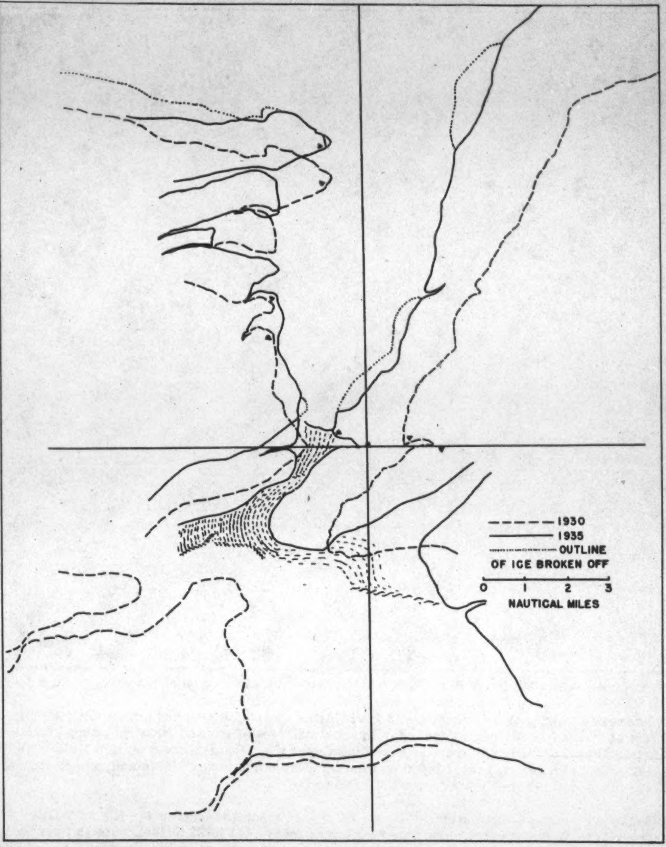


Figure 8--Bay of Whales, showing movement of ice between 1930 and 1935

side of the Bay of Whales, as observed at intervals over the period from Byrd Antarctic Expedition I (1929) down to the United States Antarctic Service Expedition (1940). An examination of the map of the edge of the shelf ice between Kainan Bay and Discovery Inlet, with particular attention to the system of cracks and the form of Lindbergh Inlet, shows that the rate of northward advance of the shelf ice at Lindbergh Inlet exceeds that along the west side of the Bay of Whales.

Rates of advance as great as 12 feet per day over a period of nine years have been measured between Discovery Inlet and the Bay of Whales, and when one considers that these observations do not take into account calving along the edge, it is not unreasonable to assume a rate of advance near Lindbergh Inlet well in excess of 12 feet per day.

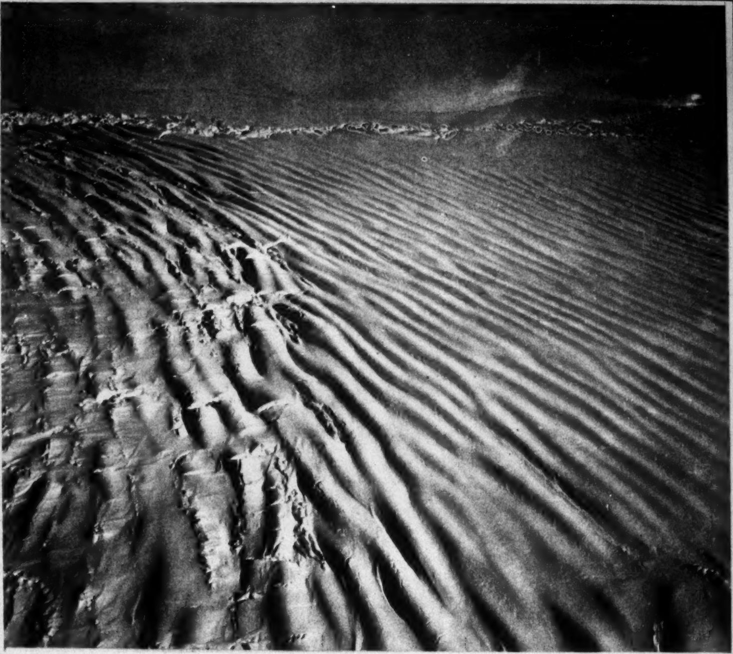


Figure 9--Bay ice from 30 to 50 feet thick folded by the motion of the thicker shelf ice

Roosevelt Island, to the southeast of Little America, which reaches a maximum elevation of 850 feet above sea level and is covered with about 550 feet of ice and snow, prevents the ice from the Marie Byrd Land Plateau from approaching the Bay of Whales except as it travels north past the east side of Roosevelt Island and then west past the north end of the Island, where it unites with the ice coming from King Edward VII Land to the east.

Surface elevation--Measurements from shipboard along the edge of the Ross Shelf Ice from Discovery Inlet to Kainan Bay show a depth ranging from 1443 to 2233 feet, with an average of 1731 feet. The position and height of this portion of the Barrier face have been measured by numerous expeditions, and the height has been found to average less than 140 feet. In general the elevation of the surface near the edge is 30 to 50 feet less than it is at a few thousand feet from the edge, because of the more rapid melting of the under surface at the edge. This decreases the buoyancy, as has already been stated and causes a general settling of the ice along the edge. This is particularly noticeable on most very large tabular icebergs. It is, therefore, not suprising that the elevations of the surface at the seismic stations between the Bay of Whales and Discovery Inlet measure 30 to 50 feet greater than measurements at the edge of the ice.

This slope is an effect associated solely with the edge of the ice and is in no way connected with any general trend in level as one proceeds south over the shelf ice. Although the Ross Shelf Ice has been traversed by many sledging parties, these have been too close either to the eastern or the western edge for there to be any real meaning in their estimates as to the difference in height of the southern and northern halves. Furthermore, the aneroid barometer, which has commonly been used, is wholly unreliable as a means for determining such small differences in elevation at such great distances from the control station. Exploration parties have in general recognized its limitations as an instrument for measuring elevation [COURT, 1945, pp. 61-66; GOULD, 1935, p. 1370; HUXLEY, 1914, v. 2, p. 410]. A critical examination of the data that have been accumulated to date on the Ross Shelf Ice shows that they are subject to very large errors and can be depended on only with regard to the most general features or for local relative values.

The data from Bolling Advance Weather Base (80°07'30"S, 163°55'W), occupied by Byrd from March 27, 1934, to October 11, 1935, provide an excellent check on the accuracy of barometric measurements of elevations in this area. GRIMMINGER and HAINES [1939, p, 7] have determined the elevation of Bolling Advance Weather Base by two different methods, using the barometric pressure data accumulated over this six-month period. By the first method, using the mean pressures at Little America and at the Advance Base, corrected for the mean temperature of the air column for this period to eliminate any error due to the cold surface layer, there was obtained an elevation for Bolling Advance Weather Base of 246 feet. The second method uses only observations made when the wind velocity at the two stations is less than six miles per hour, in order to minimize horizontal pressure gradients. By this method an elevation of 280 feet was obtained, which is probably the more accurate value. But if instead of using the mean of data taken over a six-month period, we use the mean for 24-hour periods, or, as is usually the case on trail operations, a pair of observations, we obtain values as low as 96 feet and as high as 546 feet. Since this deviation occurs for a distance of less than 100 miles, it is not surprising that very little agreement can be found among the measurements of elevation for the southern half of the Ross Shelf Ice made by the numerous field parties that have traversed it.

Data obtained by various field parties on the elevation of the shelf ice for the first 100 miles south of the Bay of Whales agree in general within plus or minus 100 feet, but there are a few isolated values that show considerable disagreement. GOULD reports [1935, p. 1969 and pl. 11] an elevation of 1032 feet at a point 45 miles south of Little America, on the basis of which he suggests that an island exists in that area, which he names Prestrud Island. During seismic sounding flights on January 5, 6, and 9, 1935, this area was traversed several times by plane. At various points on these flights the pilot would descend to within about 20 feet of the surface, and at such times the altimeter of the plane would be read. These values were later checked with the aerometeorograph carried in the plane on all flights. The figures obtained are probably accurate to within less than ten per cent, because the distances involved are less than 100 miles, the elapsed time away from a place of known elevation was never more than two hours, and flights were made on days with relatively low wind velocities for all altitudes below 10,000 feet.

The readings showed that in this region the shelf ice surface is for the most part between 150 feet and 250 feet above sea level. The only exceptions were two very small mounds at a point 25 miles south of Little America, one with an elevation of 310 feet and the other 350 feet, surrounded by snow having an elevation 190 feet, and another area of just over 500 feet above sea level at a point 40 miles south of Little America. Gould's value of 1032 feet must therefore have been obtained during a rather large horizontal pressure gradient, and it must be concluded that no true island, in the sense of land rising above sea level, exists at 79°18'S, 163°31'W, where Gould located his reading of 1032 feet.

Tide cracks--The elaborate system of cracks, generally parallel to the edge of the ice between the Bay of Whales and Discovery Inlet, has been represented on the map in Figure 5. Their positions were determined by reference to a series of overlapping aerial photographs of the Ross Shelf Ice from the Bay of Whales to Discovery Inlet (one of which is shown in Fig. 10). Although the positioning of these cracks on the map cannot be considered as accurate as that of the edge of the ice, aerial photographs taken looking west from the Bay of Whales and south at right angles to the edge of the ice give a good idea of their extent and relative positions, so that their locations on the map are reasonably accurate.

It will be observed that some of these cracks extend several miles beyond Lindbergh Inlet (see Fig. 11), a fact which shows that they antedate this inlet. The northernmost of these cracks, originating in Sunnyside Inlet, disappears about three-fifths of the way to Lindbergh Inlet and reappears about eight miles east of the Inlet, ending in the face of the Barrier just east of the Inlet. The second one, whose east end originates in Floyd Bennett Bay, has a few minor branch cracks, and a diagonal crack connecting it to the next one south, but the principal crack is continuous to Lindbergh Inlet and is in a direct line with a crack on the west side of Lindbergh Inlet which disappears a few miles to the west. The third crack originates in Chamberlain Harbor and extends continuous to Lindbergh Inlet, from the other side of which a mating crack extends a few miles farther west. A rather prominent crack starting from a point about six miles west of the south

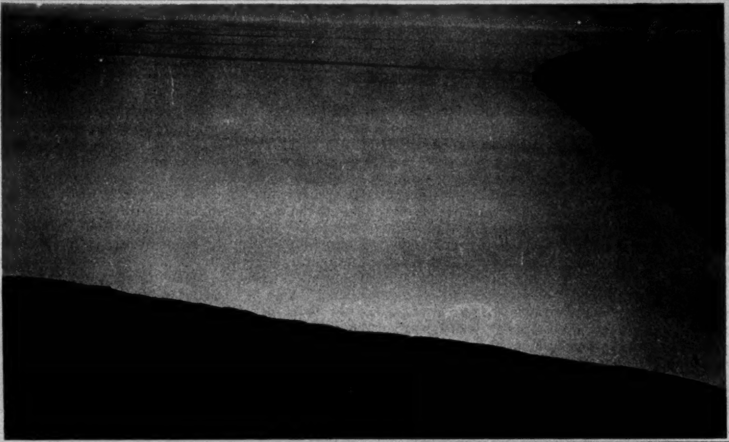


Figure 10--Parallel tide cracks in the shelf ice west of the Bay of Whales, looking southeast

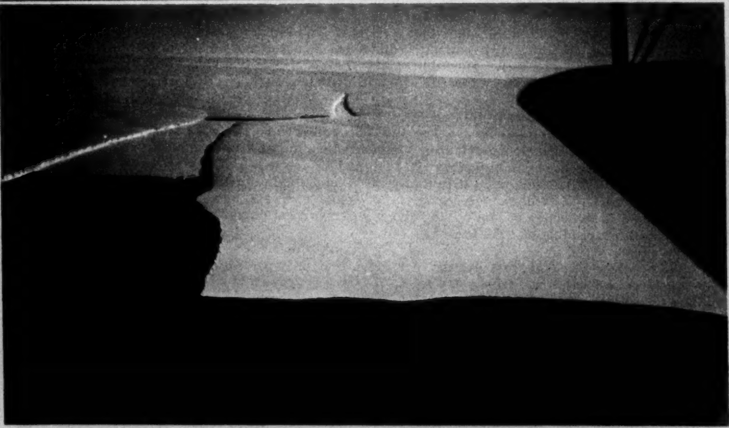


Figure 11--Lindbergh Inlet, a tension crack in the free-floating shelf ice midway between Discovery Inlet and the Bay of Whales

edge of Cape Manhue continues as a single crack for four miles and then divides into two cracks, which closely parallel each other for about 13 miles. The southern one of this pair then disappears, and the other connects with the southern tip of Lindbergh Inlet and continues on west for seven or eight miles. Another crack originates in the very small inlet in the Bay of Whales just south of Chamberlain Harbor and extends for 23 miles, then is not visible in the photograph for six miles, but again appears on the west edge of Lindbergh Inlet and is visible for six or seven miles.

Much of the present ice cliff along the front of the shelf ice was probably originally the landward side of one of these cracks. A relatively small fragment of the ice on the northern side of this crack apparently still hung on to the northern extremity of the point of ice forming West Cape of the Bay of Whales, since a depression cutting across the point clearly shows in the photographs taken in January, 1935.

In general, the nothernmost of these cracks is not apparent to a sledging party except from a shallow depression in the surface, with no indication of motion. No such information is available for those cracks more than five or six miles from the edge of the shelf ice except at their eastern end, where they are definitely active.

Contour of the bottom--The contour map presented in the preceding paper in this series covers the region immediately surrounding the Bay of Whales and constitutes the first step toward a comprehensive survey of the bottom in the shelf ice area. It is now possible to extend the area mapped to several thousand square miles, by use of information obtained at a large number of seismic stations extending from Kainan Bay south to the crest of Roosevelt Island, northwest to the Bay of Whales, west to Discovery Inlet, southeast to Bolling Advance Weather Base and again north to the Bay of Whales (see Table 1 in the preceding Part in this paper; Table 2; and Fig. 7).

The contour map shows that, starting at the southern edge of Amundsen Arm, the sea bottom reaches a depth of about 600 feet and continues at about this depth for several miles southward. The two mounds previously mentioned, rising to 310 and 350 feet above sea level, at 164°W 79°S, mark two high points in the sea bottom. The snow surface at their bases is 190 feet above sea level, and just east of them the surface is 180 feet above and the bottom 320 feet below sea level. Immediately to the west of these submerged mounds are some open crevasses or canyons estimated to be nearly a quarter of a mile wide. On one of the seismic flights over these crevasses, open cracks were observed in the bottom of one, with a number of seals on the ice; evidently the ice, in that immediate area at least, was afloat.

The low that stretches from northeast to southwest across the Bay of Whales seems to extend for some distance to the south and southeast, although at a slightly reduced depth. Between the Bay of Whales and Discovery Inlet the bottom continues at a depth of about 1600 feet for several miles under the ice and then rather sharply rises to about the level of the bottom of the ice.

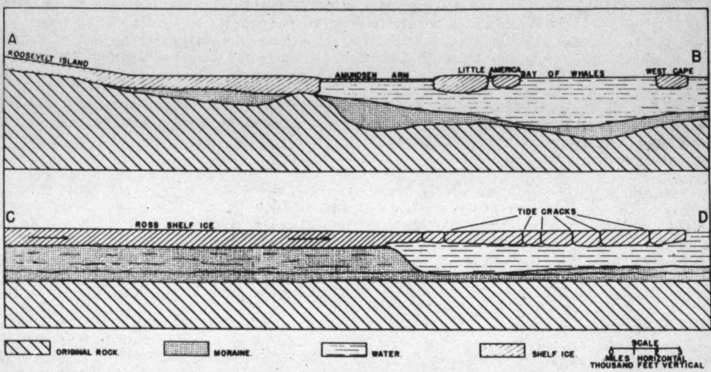
Stratification of the bottom--Most of the seismic records show marked stratification of the bottom (see Table 2). Very little of this information has been analyzed; however, because of its bearing upon the present condition of equilibrium and on the possible origin of the shelf ice, sufficient records have been analyzed to establish two vertical cross sections (Figs. 12 and 13). The positions of these two sections are shown on the map (Fig. 5). The first extends from a point A on the northwest corner of Roosevelt Island across Amundsen Arm, past Little America, and across the Bay of Whales to a point B just outside the West Cape. The other extends from a point C southeast of the southern tip of Lindbergh Inlet north past Seismic Stations 89, 90, and 106, and to the edge of the shelf ice at a point D just east of Lindbergh Inlet.

An examination of these records shows that there is a deposit on the bottom along Stations 102 to 116, inclusive, a few miles from the edge of the ice. The thickness of the deposit averages 363 feet and its surface is quite uniform except at points of maximum current, as at Stations 100, 115, and 116. There are a number of minor reflections from levels between the bottom of the water and the second major reflection. This second major reflection appears to be from the original rock surface. Between the Bay of Whales and Discovery Inlet the depth of this second reflecting surface varies from 1885 feet to 2266 feet below sea level. The smoothness of the records below this depth, and the absence of minor reflections, indicate that it is a thick layer of uniform and undisturbed rock. Section A-B shows that the elevation of this lower reflecting surface is quite irregular, rising to above sea level at Roosevelt Island, but that the irregularities are smoothed over by the moraine which has been laid down over it, the top surface of which has a rather uniform slope of 100 feet per mile from Roosevelt Island to the low in the Bay of Whales.

Summary of data--Let us now review briefly the features of the Ross Shelf Ice which have been established with a reasonable degree of certainty by direct observation:

(1) The accumulation of snow and frost on the surface of the shelf ice is at a maximum along the northern edge, near open water.

(2) Between Discovery Inlet and the Bay of Whales the top surface of the Ross Shelf Ice slopes up from the edge, reaching a maximum elevation along a line from one to three miles from the



Figures 12 and 13--Vertical section of shelf ice and moraines along lines indicated by dashed lines AB and CD in Figure 5

edge, and then gradually slopes down so that at 10 to 25 miles from the edge it is 30 to 50 feet lower than it is at two miles from the edge.

(3) Although no exact values are known for the elevation of the southern half of the shelf ice, such values as exist are not greatly different from those for the northern half, which are known to a much greater accuracy.

(4) The northern edge of the shelf ice breaks off, to form large tabular icebergs of the kind common in Antarctic waters. Examination of the edge of the shelf ice and of bergs which have overturned shows no evidence of glacial material.

(5) The thickness of the ice at the edge of the floating portion of the Ross Shelf Ice east of Discovery Inlet averages about 525 feet, whereas at a point from one to three miles from the edge it averages about 755 feet. From this maximum the thickness again decreases gradually over the next ten miles to the southward, reaching a minimum of less than 500 feet in places. South of this line the thickness again increases quite sharply to about 700 feet (see Fig. 13).

(6) A current of from one to three knots enters Okuma Bay and moves in a southwesterly direction, partly along and partly under the ice at Kainan Bay. It enters the Bay of Whales along the Barrier or emerges from under the shelf ice on the east side of the Bay, particularly through Eleanor Bolling Bight, crosses the Bay in a southwesterly direction, and again goes beneath the ice along the west side of the Bay. The current then travels west under the ice past or south of Lindbergh Inlet and out from under the ice in a northwesterly direction through Discovery Inlet.

(7) A three-foot tide exists at Ross Island at the western edge of the shelf ice, and a tide of unknown but probably equal or greater magnitude exists at the Bay of Whales.

(8) A system of parallel cracks exists in the 15-mile wide portion of the northern edge of the shelf ice east of Discovery Inlet. There is no apparent motion along those cracks nearest the northern edge of the shelf ice, but those farther south are known to be active at their eastern ends. Most of these cracks extend west as far as Lindbergh Inlet, and some of them extend several miles beyond.

(9) The bottom of the Ross Sea continues at about the same depth back under the Ross Shelf Ice to a point about ten miles from the edge, where it rises until it is essentially in contact with the bottom of the shelf ice. At points south of this rise in the sea bottom the seismic instruments continue to record reflections from a surface at the same depth as that of the sea bottom north of the rise.

(10) The average rate of northward advance of the shelf ice between Discovery Inlet and the Bay of Whales exceeds 12 feet per day. The maximum velocity is found near Lindbergh Inlet, where the daily advance is probably well in excess of 12 feet.

(11) The shelf ice immediately south of Discovery Inlet is grounded below sea level, and since the surface to the south and southeast of the Inlet slopes up to an elevation of more than 200 feet, it is probably grounded over a considerable area.

(12) The major portion of the shelf ice east of 164° W and extending from Amundsen Arm to 80° S (the southern limit of our measurements) is grounded all the way to the Rockefeller Plateau. The contact of the ice with ground occurs below sea level except over Roosevelt Island, which reaches an elevation above sea level of 850 feet.

Discussion and conclusions--Some of the information just summarized has long been known but has only now received confirmation, as a result of the scientific activities of the Byrd Antarctic Expedition II. Some of the existing impressions have been extended and some disproved, and a number of entirely new facts have been brought to light. Before the complete picture for the Ross Shelf Ice is at hand, a great many more seismic stations will have to be occupied. But data that have been thus far obtained are sufficient to justify an attempt at arranging the facts into a single structure that is consistent and in agreement with all of the known facts. It is now possible to outline more clearly the condition of equilibrium which exists today, to explain the causes for the various surface features, to determine the factors which govern the movement of the shelf ice, and to postulate its probable origin.

There are two possible explanations for the apparent absence of glacial material in the shelf ice and for its uniform character. One possibility is that all of the solid ice from the glaciers feeding the sheet from the south is melted off from underneath and is replaced by the accumulation of snow on the top surface. Another possible explanation is that the contribution from the nearby broad, flat, land-locked glaciers consists originally of firn, with only glacial drift embedded in the bottom surface.

The fact that the lower part of the shelf ice either consists of or contains some kind of high-density material is indicated by the variation in the per cent of ice floating above sea level. For instance, where the ice comes directly from a grounded area just south of Discovery Inlet, only 11.7 per cent is floating above sea level, whereas the ice on the north side of the inlet floats with 14 to more than 16 per cent above water. That on the north side is the same ice as on the south, but it has been afloat long enough for a considerable amount of the heavier part to have melted off the bottom. At stations near the edge of the floating ice, such as station 102, the high percentage of ice above sea level is probably caused by the slow rate at which the whole mass settles after ice has been melted from the lower surface.

The vertical cross sections of the Ross Shelf Ice, one across the Bay of Whales to Roosevelt Island, and the other south into the shelf ice east of Lindbergh Inlet, throw a great deal of light upon the condition of equilibrium that exists today. The slope along the edge has already been explained by the accelerated melting at the edge. The occurrence of a maximum in surface elevation and ice thickness at two miles from the edge has been attributed to the high rate of precipitation near open water.

An examination of the contour map of the bottom, with the ocean currents in mind, shows that these currents follow the path of maximum depth, which also parallels the northern face of the moraine that has been built up under the ice. This current underneath the ice where it projects out over the moraine causes a maximum amount of melting to occur along this path, thereby causing the major portion of the glacial material being carried by the shelf ice to be deposited on the forward edge of the moraine.

This process is sufficient in itself to account for the origin of the Ross Shelf Ice. The moraine, essentially in contact with the bottom of the shelf ice, would protect it against being broken up by heavy seas; and the ice in turn, moving over the top surface of the moraine, would prevent the deposit from building up above a certain level, for two reasons. First, as the top of the moraine comes into contact with the bottom of the floating ice, the circulation of water under that portion of the ice would be reduced, the rate of melting would decrease, and little glacial material would be deposited. In the second place, any such material that was deposited, if high enough to interfere with the movement of the ice, would be dragged forward and dumped over the seaward edge of the moraine. As the ice sheet extended over greater and greater distances, it would be aided in its forward motion by the action of the tide, which tends to lift the floating, or nearly floating, ice once every 25 hours.

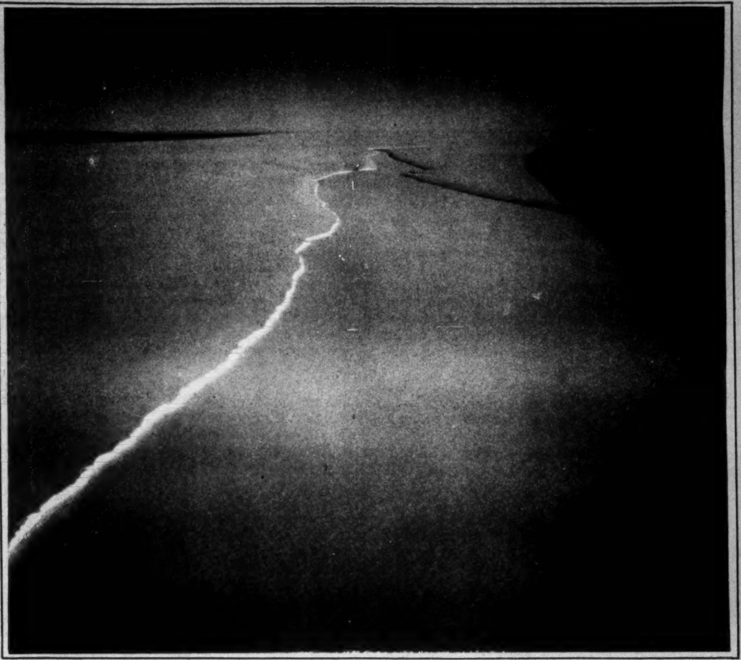


Figure 14--Discovery Inlet, looking east

Now if, in addition to this process, we take into account Roosevelt Island and other elevations under the shelf ice close to, or possibly above, sea level, such as the area just south of Discovery Inlet, the origin of the Ross Shelf Ice loses most of its mystery, and it becomes unnecessary to postulate conditions greatly different from those now existing, to explain the origin of the shelf ice and the establishment of its present equilbrium.

Now let us consider the system of parallel tide cracks existing between Discovery Inlet and the Bay of Whales. The broad sheet of floating ice, free to rise and fall with the tide, extending beyond the edge of a moraine in contact with the bottom of the ice, would tend to break off this overhanging ice along the forward edge of the moraine, where the ice thickness decreases from about 700 to 500 feet.

One might at first expect that there should result a considerable difference in elevation of the top surfaces of two sheets of ice which differ so much in thickness, but one must remember that the ice which has been removed from the 500-foot thick part is that portion having the greatest density, and in addition containing the glacial material. There is undoubtedly some motion along the entire length of these freshly formed cracks, and such activity is known to occur at their eastern ends although no such observations are available for other localities.

Whenever the cracks have advanced far enough beyond the forward edge of the moraine so that both sides are entirely free-floating, they will again freeze together at sea level, and any open portion above sea level will either be filled in with drifting snow or, what is more likely, be bridged over. This opening, plus a thinning caused by the tendency of the water to melt the ice more rapidly along these cracks, causes a line of weakness which is instrumental in the formation of the icebergs occasionally reported in the Antarctic, often more than 50 miles in length

The melting of the ice along these cracks, particularly where the water enters under the ice along the west side of the Bay of Whales, is the process by which the bays, inlets, ets., along the west side of the Bay are formed. It will be observed from the map that some such feature has developed at the end of each of these cracks.

The fact that this ice is land-locked to both the east and west prevents these cracks from opening up to any great width and keeps the pieces of ice from drifting out to sea. This fact, furthermore, plays a basic part in the origin of Lindbergh Inlet, which is obviously a tension crack such as forms in the edge of a piece of ice locked at both ends and being forced ahead in the middle.

Discovery Inlet (Fig. 14) is another feature which is likewise very much to be expected, in view of the conditions we now know to exist. As the ice sheet advances northward beyond the region where it is grounded just south of the inlet, the current flowing along the forward edge of the moraine has reduced the thickness of the ice along that line and a tidal crack has developed. Since the ice to the east of Discovery Inlet is relatively free-floating and is farther from the edge of the moraine, the crack did not lengthen out for a great distance, and the piece of ice north of this crack remained attached to the main part of the shelf ice. The shelf ice to the east of Discovery Inlet, to which that on the north side of the Inlet is attached, has a greater velocity toward the north than does the ice on the south side of the Inlet; and as a result, Discovery Inlet continually increases in width.

The fact that the whole of Discovery Inlet is shifting to the north is confirmed by the changes observed in the depth of the water in the Inlet. Measurements made from the Bear of Oakland in 1934 ranged from 1560 to 1750 feet, whereas in 1924, the whaler, Sir James Clark Ross anchored in Discovery Inlet in only 1000 feet of water, a figure which agrees very closely with the depth measured at Seismic Station 91.

Aerial photographs clearly show a depression in the surface of the snow extending south from Kainan Bay to the crevassed area north of Roosevelt Island. This resembles very closely the depressions along the parallel cracks west of the Bay of Whales, and it is undoubtedly a tide crack, since the condition existing here is similar to that west of the Bay of Whales. The ice, in its westward motion, comes from higher land or a moraine the western edge of which lies along a north and south line just east of Kainan Bay. Furthermore, Kainan Bay has been formed in a manner very similar to that of the bays and inlets along the west side of the Bay of Whales, that is, by the water entering under the ice and causing accelerated melting at the edge of the ice, especially where a crack exists. In this case the process is aided by the fact that the rate of motion of the ice in a westerly direction is greater at ten miles from the edge of the shelf ice than it is at the edge. This faster-moving part carries with it the ice on the west side of Kainan Bay, causing the Bay to widen.

Eleanor Bolling Bight is an example of a related phenomenon, the formation of a small bay as a result of the current's following a channel under the ice and melting the ice above it to such a degree that the opening cuts clear through the shelf ice. In a bay thus formed there is a gradual slope of the surface down to a relatively low barrier at the edge of open water. The depression in the surface of the shelf ice can be traced in aerial photographs for a long way beyond the bight, following the low in the bottom.

It is easy to see, from the information which has been given, why the Bay of Whales persists in the same place. While a large piece of ice may break away at any one of a number of points, enlarging the Bay, the likelihood is that the next very large piece to go out will be along the east side and that it will open up the Bay clear back to the southern edge of Amundsen Arm and as far east as Kainan Bay, the east side of which will then form the new East Cape.

The present seismic measurements of the Ross Shelf Ice have provided the first real information on its thickness, the thickness of the water layer under the floating portion, the contour of the bottom under the ice, the existence of large moraines, and the contour of the undisturbed rock surface below. It has been shown that a much larger proportion of the shelf ice is actually or practically in contact with the bottom than has hitherto been suspected. These data have provided the answers to many of our questions relative to the origin of the shelf ice and the persistence of its characteristic features.

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USE OF PITOT TUBE TO COMPENSATE FOR PRESSURE DEFICIENCY CAUSED BY WIND ON MOUNT WASHINGTON, NEW HAMPSHIRE

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Abstract--By virtue of the Bernoulli effect, the wind blowing over the summit of Mt. Washington, New Hampshire, causes the station barometric reading to be less than the pressure at the same level in the free air near the summit but away from the influence of the mountain. The object of this paper is to determine the amount of pressure fall that results from the Bernoulli effect and to show how it may be compensated for to a good degree of approximation by use of a pitot tube connected to the barometer.

The pressure deficiency produced by the wind at Mt. Washington has been ascertained by correlating barometric readings on the mountain with comparable data reported by surrounding low-level radiosonde stations. The latter data were derived by interpolation from synoptic charts giving pressures of the 5000-foot plane or heights of the 850-millibar constant-pressure surface. A curve of pressure correction to overcome the specified deficiency in barometric reading has been prepared, giving the correction as a function of wind velocity. This curve showed that the flow of air over the mountain causes the observed barometric pressure on the summit to decrease relative to free-air pressure nearly in proportion to V^2, where V = wind velocity observed on the summit. This fact suggested to the author that the impact pressure of the wind ($\rho V^2/2$, where ρ = air density) available from a pitot tube vaned into the wind might be used to compensate automatically for the pressure deficiency produced by the wind, since both impact pressure and pressure deficiency apparently are functions of V^2. A vaned pitot-tube assembly was built and mounted on the Observatory tower freely exposed to the wind. Tubing was used to connect the pitot tube to a fixed-cistern mercurial barometer and to a pressure-tight box containing a standard microbarograph. The impact pressure of the wind thus imposed directly on both the barometer and the microbarograph is found to compensate approximately for the deficiency in pressure due to the wind blowing over Mt. Washington. The pressure observed at the station, with the pitot tube connected to the barometer, was compared to the local free-air pressure derived by interpolation from the upper-air synoptic charts. Tables of frequency of various discrepancies between these two pressures are given. These tables show that zero (0) discrepancies occur with greatest frequency, although a discrepancy as large as eight millibars has been observed out of 176 comparisons. It is believed that a major proportion of each large discrepancy results from errors in location of the isograms on the upper-air charts that served as a source for the comparative data. Judging by the data available, the mean discrepancy in station pressure found when using the pitot tube with the barometer at Mt. Washington is of the order of one millibar.

Introduction--A paper written in 1944 by the author [see "References" at end of paper, FALCONER, 1944] with reference to data secured at the summit of Mt. Washington, New Hampshire, presented a curve indicating a correlation between (P_2 - P_1) and V, where P_1 = apparent station pressure (as influenced by the Bernoulli effect); P_2 = free-air pressure uninfluenced by the mountain, for a point in the free air at the level of, and near to, the station; and V = wind velocity observed at a height of 37 feet above the summit. We apply the term "pressure deficiency" to the quantity (P_2 - P_1). To obtain some idea of the correlation between the aforementioned quantities, the current wind velocity, V, was plotted against (P_5 - P'_5), where P'_5 = barometric pressure as observed at Mt. Washington reduced to the 5000-foot level; and P_5 = barometric pressure at the 5000-foot level obtained for the location of Mt. Washington by interpolation between isobars on mean monthly 5000-foot charts as published in the Monthly Weather Review for the years 1941-42-43.

A smoothed curve of (P_5 - P'_5) plotted against V, based on these data, is presented in Figure 1. This curve is labeled "Correction Curve No. 1" in the Figure. It was assumed that to a sufficiently close degree of approximation (P_5 - P'_5) = (P_2 - P_1). Using the current wind velocity at Mt. Washington as an argument, Correction Curve No. 1 was found to yield corrections, (P_5 - P'_5), which when applied to the station pressure, P_1, gave results in close agreement with the local free-air pressure, P_2. For the data reported on in the 1944 paper, the station pressures were determined by means of a Fortin barometer located in the Mt. Washington Observatory building.

On March 15, 1945, the United States Weather Bureau authorized Mt. Washington Observatory to transmit for each synoptic observation, the 5000-foot pressures based on the corrected station pressure as determined by using Correction Curve No. 1. Table 1 shows the results obtained using this curve. Of the total 331 comparative observations including all wind directions, the average discrepancy regardless of sign proved to be 0.91 mb. In this instance, the number of observations with plus or minus one mb or less discrepancy was 270 out of the 331, or 81 per cent of the total. Sharply contrasting with this was the situation when Correction Curve No. 1 was not used; for then the uncorrected Mt. Washington pressure reduced to the 5000-foot plane gave an average net discrepancy of - 2.2 mb. On the average the original correction curve tends to give values slightly too great (see Tables 1 and 4) as confirmed in an analysis of our data at the Eighth Weather Headquarters, U. S. A. A. F., at Grenier Field, New Hampshire. That Headquarters suggested a new curve which gave less correction than did Correction Curve No. 1 for wind speeds above 50 mph.

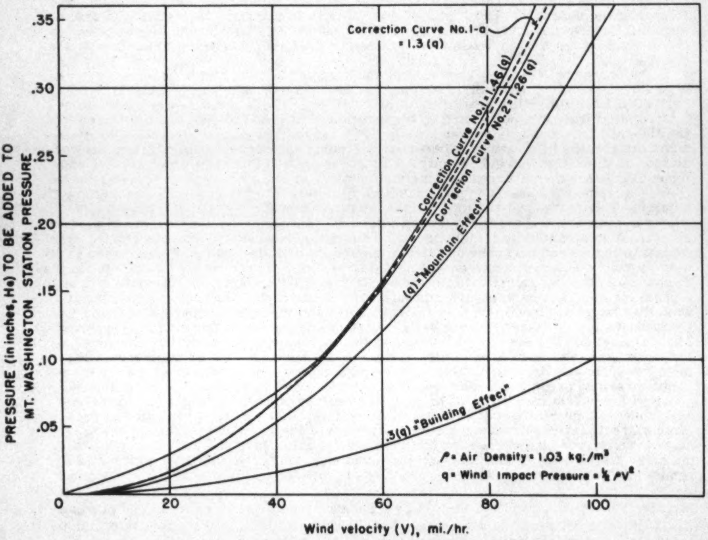

Fig. 1--Smoothed curve of (P_5 - P_5') plotted against V

Approximate equation of the correction curve--Except for velocities less than 40 mph at the station, the extrapolated correction curve presented in the author's previous paper [FALCONER, 1944] and Correction Curve No. 1 (see Fig. 1) may be represented very nearly by an empirical equation of the form

$$\Delta P = C_1 V^2 \quad (1)$$

where ΔP = correction of pressure based on Fortin barometer reading at Mt. Washington, in mb; V = wind speed in mph; and C_1 = approximately a constant = 0.0015, applying to the average conditions for winds over 40 mph.

This suggests that the correction is nearly proportional to the impact pressure of the wind, $\rho V^2/2$, where ρ = air density (density varies only slightly on Mt. Washington), V = wind speed, in consistent units. If such a proportionality exists, then

$$\Delta P = C(\rho V^2/2) \quad (2)$$

where C is an appropriate constant. For cgs units (ΔP in dynes, V in cm/sec), with $\rho = 0.00103$ grams per cubic centimeter (the mean annual value for Mt. Washington), and C_1 as given above, the value of C becomes 1.46. Thus ΔP would be 1.46 × the impact pressure of the wind.

Table 1--Comparison of Mt. Washington 5000-foot pressures using Correction Curve No. 1 and the interpolated 5000-foot pressures from the East Boston map

Wind direction	Number of observations	Sum of positive discrepancies	Sum of negative discrepancies	Total discrepancy	Average discrepancy
		mb	mb	mb	mb
West	177	77	69	146	0.80
West-southwest	8	5	2	7	0.87
Southwest	37	30	15	45	1.22
South-southwest	4	4	0	4	1.00
South	15	8	3	11	0.73
South-southeast	2	1	0	1	0.50
Southeast	14	7	4	11	0.79
East	10	8	4	12	1.20
Northeast	6	6	2	8	1.30
North-northeast	2	0	2	2	1.00
North	3	1	1	2	0.66
North-northwest	5	0	4	4	0.80
Northwest	37	20	12	32	0.86
West-northwest	11	8	9	17	1.60
Totals	331	+ 175	- 127	302	0.91
Discrepancies using uncorrected pressure					
Totals	331	+ 23	- 709	732	2.2

Since the uncorrected pressures were observed by means of a Fortin barometer in the Mt. Washington Observatory building, the discrepancies under consideration must be attributed to the joint effects of the Mountain and the building.

The "mountain effect" and the "building effect"--Mt. Washington acts as a constriction to the flow of air over and around it, and, due to the relationship involved in Bernoulli's theorem, a reduction in barometric pressure depending on the wind velocity should be expected at all points of constriction. As indicated in Table 2, the Mountain is somewhat symmetrical in shape so that the reduction in pressure on the summit with a given wind velocity should be fairly constant for any wind direction. For purposes of discussion, this effect of the mountain in reducing the pressure will be referred to as the "mountain effect."

In addition to the "mountain effect," there is a further lowering of the pressure (in the case of Mt. Washington) caused by what we may call the "building effect." This effect is in existence at all stations to some degree. In a memorandum from L. P. Harrison, United States Weather Bureau, Washington, D. C., it is stated: "Experiment has shown that to a close degree of approximation

$$P_s - P_b = Kq_b \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (3)$$

where P_s = static pressure at the location of the station; P_b = pressure measured within the building on a standard Fortin barometer; $q_b = \rho V_b^2/2$ = impact or velocity pressure representative of the building where ρ = air density at this location, and V_b = wind velocity; and K = a function of local wind direction and vertical velocity of air; ratio of openings in buildings to closed exterior surface; size, shape, length, and roughness of the connections between openings and interior of building; location of the barometer in the building relative to the openings and wind direction; shape and proportions of the dimensions of the building; Reynolds number ($V_b L\rho/\mu$, where L = a representative linear dimension of the building and μ = absolute viscosity of the air); fine-grained and large-scale turbulence of the air; artificial ventilation or forced draft within the building; etc.

"If the openings are chiefly on the leeward side, K is positive and a suction is produced within the building. On the other hand, major openings on the windward side will cause K to become negative, corresponding to an excess pressure within the building as compared with static pressure.

According to available information, air leakage resulting from the usual small openings around windows, doors, skylights, and eaves will give rise to a value of K ranging from ± 0.25 to ± 0.35 for cgs units, including pressure in dynes. With large openings, for example, as in the case of open barns or hangars, the factor may be larger (possibly ± 0.6), depending on wind direction with relation to openings.

Table 2--Mt. Washington, New Hampshire - 6288 feet

Direction from station	Average slopes (grades) from station to					
	500 ft	1000 ft	1500 ft	2000 ft	2500 ft	3000 ft
	below station					
North	0.23	0.32	0.36	0.39	0.34 and 0.10	. . .
North-northeast	0.16	0.23	0.27	0.29	0.24 and 0.09	. . .
Northeast	0.17	0.16	0.18	0.22	0.24	0.25
East-northeast	0.36	0.29	0.36	0.22	0.25	0.27
East	0.45	0.39	0.33	0.39	0.32	0.30
East-southeast	0.42	0.46	0.37	0.40	0.43	0.33
Southeast	0.42	0.46	0.45	0.44	0.27	0.28
South-southeast	0.38	0.44	0.45	0.22	0.24	0.25
South	0.38	0.19	0.20	0.20	0.23	0.23
South-southwest	0.31	0.21	0.23	0.27	0.25	0.23
Southwest	0.33	0.29	0.14	0.17	0.17	0.15
West-southwest	0.33	0.36	0.39	0.39	0.26	0.27
West	0.29	0.39	0.42	0.46	0.36	0.36
West-northwest	0.29	0.17	0.31	0.36	0.34	0.27
Northwest	0.25	0.31	0.19	0.22	0.25	0.20
North-northwest	0.26	0.40	0.17	0.15 and 0.11	0.14	0.17

Table 3--Values of $(P_s - P_b)$ for various values of V_b

V_b	$\pm (P_s - P_b)$
mph	mb
25	0.19
50	0.77
75	1.74
100	3.07
125	4.83

"With a mean annual pressure and temperature of 800 mb and 28°F, respectively, and assuming 80 per cent relative humidity, the mean air density on Mt. Washington is 0.00103 g/cm^3. Taking K = 0.3 (for cgs units) we find, with this value of density, and for P_s and P_b expressed in millibars, $P_s - P_b = \pm 0.000000154 V_b^2$ mb, where V_b is in cm/sec. The values in Table 3 result."

The Mt. Washington Observatory is so constructed that it is believed a suction is produced and the pressure consequently lowered within the building for practically any wind direction and especially with the prevailing southwest, west, and northwest winds. The tower on which instruments are exposed is 30 feet high by six feet square and is at the northeast end of the main Observatory building, being an integral part of it. There are two loosely-fitting doors, one at the top and one at the bottom of the tower, which are the only means of closing off the standard Fortin barometer in the downstairs weather room from the direct effects of the wind blowing across the top of the tower. The door to the outside is at the bottom of the tower also and approximately faces the northeast. There are two windows on the southeast side of the main building, which are normally open except during strong winds from the south, southeast, east, and northeast.

It is conceivable that when winds are blowing from the directions north, northeast, east, southeast, and south, the suction produced by wind blowing across the top of the tower might be modified by wind blowing into openings on the southeast and northeast sides of the building. There are also, of course, varying effects of any of the smaller openings in the building, such as around closed windows, depending on whether the building is absolutely bare or whether it is covered partially or completely with a coating of ice, which is the case during most of the winter months.

Data collected to date show that the single correction curve (No. 1) gives very good results for all wind directions, although, theoretically, a different curve should perhaps be used for some directions. Because winds from the north, northeast, east, and southeast occur so infrequently on Mt. Washington, some time will be required to be sure that another curve would give more accurate results for these directions at all times.

If the barometer is located inside the building, the correction curve then has to compensate for the effect of the mountain plus that of the building, and can be represented in an equation as

$$\Delta P = \Delta P_m + \Delta P_b \quad \ldots\ldots (4)$$

where ΔP_m = correction necessary to compensate for mountain effect; and ΔP_b = correction necessary to compensate for building effect.

Equation (3) may also be written as

$$\Delta P_b = K(\rho V^2/2) \quad \ldots\ldots (5)$$

so that by substituting (2) and (5) in (4) and solving for ΔP_m we have

$$\Delta P_m = (C - K)(\rho V^2/2) \quad \ldots\ldots (6)$$

Considering that the previously-mentioned values of C in (2) and K in (3) are representative, we have, for cgs units, the empirical result

$$\Delta P_m = (1.46 - 0.3)(\rho V^2/2) \doteq 1.16(\rho V^2/2) \quad \ldots\ldots (7)$$

Thus we see that if the value of K remains constant, the mountain effect is responsible for a reduction in pressure roughly equivalent to $\rho V^2/2$. Accordingly, we find on the basis of the mean data embodied in Correction Curve No. 1 and in Table 3, that on the average the amount of pressure deficiency (ΔP_m) produced by the wind blowing over the summit is approximately equal to the impact pressure of the wind.

To show this graphically, the impact pressure of the wind ($\rho V^2/2$) has been plotted in Figure 1 using a value of ρ equal to the mean annual air density at Mt. Washington. The curve of impact pressure is labeled "q = mountain effect." Considering that the building effect is $0.3(\rho V^2/2)$, a curve to represent this, labeled "0.3 q = building effect," is also shown in Figure 1. If values of the building effect are added to values of the mountain effect, the result is Correction Curve No. 1a of Figure 1. It can be seen that this curve is remarkably close to the original Correction Curve No. 1, although the latter was drawn before the above considerations had been made.

Difficulties in use of a correction curve--While the use of Correction Curve No. 1 has rendered the corrected Mt. Washington pressure data more representative of the local free-air pressures, there are also certain difficulties in its application. These difficulties are:

1. The use of a correction curve involves an average reading of a barometer and of an anemometer, simultaneously, with the possibility of erroneous readings on one or both instruments. Accurate average readings of the Fortin barometer are practically impossible to obtain during the frequent periods of high winds on Mt. Washington, owing to severe pumping of the barometer. After the readings have been obtained, several corrections are necessary before the corrected station pressure is derived.

2. There is the possibility that when more data have been gathered and analyzed, a different curve or curves for some directions will be found more desirable. It might then be necessary to determine wind directions to a greater degree of accuracy. It is also true that the use of other curves for different directions might become void if for any reason the openings in the building were altered, thus changing the "building effect."

3. There is no way to correct the barograph trace by using merely a correction curve. The trace can be corrected for wind velocity at each three-hourly observation time, but what has happened between these times cannot be known since the velocity may vary greatly. By comparing three-hourly corrected pressures it can be said that the pressure is now higher, lower, or the same as at the previous observation but irregularities between observations are not known. Actually, the uncorrected barograph trace is often unrepresentative in its indication of pressure tendency because of the variable unknown pressure deficiencies stemming from variable wind velocities.

Use of pitot tube to correct pressure automatically--To overcome some of the difficulties in using the correction curve, the author, in March 1945, discovered that a pitot tube, with which we were experimenting at the time, might be used to correct the pressure as affected by the wind automatically. A Bowen fixed-cistern barometer was available at the station, and the tube leading from the pressure opening of the pitot tube was connected to the available opening in the top of the cistern of the Bowen barometer.

Table 4--Summary of comparisons of automatically-corrected pressures at Mt. Washington, reduced to the 5000-foot level, with 5000-foot pressures interpolated from maps at East Boston, Massachusetts, and Grenier Field, New Hampshire, and of comparisons between the interpolations from East Boston and Grenier Field maps

Wind direction	Number of observations	Discrepancies								
		Mt. Washington minus East Boston			Mt. Washington minus Grenier Field			East Boston minus Grenier Field		
		Positive	Negative	Mean	Positive	Negative	Mean	Positive	Negative	Mean
		mb	mb	mb	mb	mb	mb	mb	mb	mb
West	25	6	15	0.8	4	16	0.8	6	9	0.6
Southwest	7	1	5	0.9	5	1	0.9	8	0	1.0
South-southwest	1	1	0	1.0	0	0	0.0	0	1	1.0
South	4	0	0	0.0	0	5	1.2	0	5	1.2
Southeast	6	1	4	0.8	3	2	0.8	5	1	1.0
East	2	2	1	1.5	1	1	1.0	0	1	0.5
Northeast	1	0	2	2.0	0	1	1.0	1	0	1.0
North	1	1	0	1.0	1	0	1.0	0	0	0.0
Northwest	4	4	0	1.0	0	0	0.0	0	4	1.0
Totals	51	+ 16	- 27		+ 14	- 26		+ 20	- 21	
Totals (+ and -)		43 mb			40 mb			41 mb		
Average discrepancy (51 observations)				0.8			0.8			0.8

Table 5--Frequency table showing frequency of various discrepancies in 5000-foot reduced pressure at Mt. Washington, where the station pressure was corrected on the one hand by the use of Correction Curve No. 1, and on the other hand by the use of the pitot-tube automatic correction. Mt. Washington pressures are reduced to 5000-foot pressure and compared to interpolated 5000-foot pressures at the Mt. Washington location determined from 5000-foot maps drawn at East Boston, Massachusetts, and Grenier Field, New Hampshire

Discrepancy	Mt. Washington minus East Boston map				Mt. Washington minus Grenier Field map				East Boston map minus Grenier Field map	
	Curve No. 1		Automatic correction		Curve No. 1		Automatic correction			
	No. of obs.	Pct of total	No. of obs.	Pct of total	No. of obs.	Pct of total	No. of obs.	Pct of total	No. of obs.	Pct of total
(to nearest mb)										
+ 5	..	..	..	..	..	..	..	..	1	2
+ 3	2	4	..	..	2	4	1	2	..	..
+ 2	6	12	2	4	3	6	1	2	..	..
+ 1	11	22	12	24	9	18	9	18	9	18
0	18	35	16	31	30	59	25	49	21	41
- 1	11	22	15	29	2	4	8	16	16	31
- 2	3	6	6	12	4	8	4	8	3	6
- 3	..	..	..	..	..	..	2	4	..	..
- 4	..	..	..	..	1	2	1	2	1	2
Total obs.	51		51		51		51		51	
Discrepancy of ± 1 mb or less		79		84		80		82		90

With this arrangement, and the pitot tube vaned into the wind, the impact pressure of the wind is imposed upon the mercury in the barometer at all times, causing the instrument to show an apparent pressure increase equal to the dynamic pressure of the wind, $\rho V^2/2$. With the Bernoulli effect acting to reduce the pressure on the mountain approximately by the amount $\rho V^2/2$, and the impact pressure from the pitot tube causing the mercury to rise by a nearly equivalent amount, the two effects very nearly cancel each other, resulting in a pressure indicated by the barometer approximately equal to the pressure that would exist if the mountain were not there. The fact that the barometer, in this arrangement, is vented only to the outside free air at once eliminates any need of correcting for the lowering of pressure caused by action of wind on the air in the building.

Results obtained using automatic-correction method--From March 1 to August 15, 1945, two sets of comparative data were tabulated, namely, the automatically-corrected Mt. Washington pressure reduced to 5000 feet, and the interpolated values of 5000-foot pressure for the location of Mt. Washington as determined from 5000-foot maps drawn at Grenier Field, New Hampshire, and East Boston, Massachusetts. The results for various wind directions are shown in Table 4. It should be noted that the discrepancies between the automatically-corrected Mt. Washington pressure reduced to 5000 feet and the interpolated value from either of the two maps is, for all practical purposes, no greater than the discrepancies between the two maps. In other words, the automatically-corrected pressure on Mt. Washington is within approximately the same limits of accuracy as the pressure for a fixed point found by interpolating between isobars on synoptic charts constructed by different persons. The tabulations show that there are more negative discrepancies than positive ones using the automatic correction method, while there were a greater number of positive than negative discrepancies using the original correction-curve method.

Table 6--Summary of comparisons of heights of the 850-millibar constant-pressure surface, computed from automatically-corrected Mt. Washington pressures, with 850-millibar heights interpolated from maps at East Boston, Massachusetts, and Grenier Field, New Hampshire, and of comparisons between the interpolations from East Boston and Grenier Field maps. Values indicate positive, negative, and mean discrepancies in feet, except that final averages are reduced to millibars

Wind direction	Number of observations	Discrepancies: Mt. Washington minus East Boston			Discrepancies: Mt. Washington minus Grenier Field			Discrepancies: East Boston minus Grenier Field		
		Positive	Negative	Mean	Positive	Negative	Mean	Positive	Negative	Mean
		ft	ft	ft	ft	ft	ft	ft	ft	ft
West	58	1110	814	33	758	654	24	640	715	23
West-southwest	5	70	48	24	25	41	13	40	130	34
Southwest	10	130	167	30	121	208	33	80	130	21
South-southwest	1	0	46	46	0	36	36	10	0	10
South	1	0	44	44	0	44	44	0	0	0
Southeast	7	295	27	46	295	67	52	50	90	20
Northeast	1	0	8	8	0	8	8	0	0	0
North-northeast	1	0	31	31	0	11	11	20	0	20
North	2	19	73	46	9	23	16	40	10	25
Northwest	33	743	331	36	555	288	26	280	415	21
West-northwest	4	66	72	35	32	98	32	30	50	20
Totals	123	+ 2433	- 1661		+ 1795	- 1478		+ 1190	- 1540	
Totals (+ and -)		4094 ft			3273 ft			2730 ft		
Average		33 ft			27 ft			22 ft		
Average discrepancy (breakdown)		1.0 mb (+ 0.6 - 0.4)			0.8 mb (+ 0.45 - 0.35)			0.7 mb (+ 0.3 - 0.4)		
Previous comparative data using reduced 5000-foot pressure value for 51 observations (breakdown)		0.8 mb (+ 0.3 - 0.5)			0.8 mb (+ 0.3 - 0.5)			0.8 mb		

The above facts probably show up best in Table 5. For this set of data, using 5000-foot pressure reductions based on 51 observations, Correction Curve No. 1 yielded better results than are later found with data using the height of the 850-millibar constant-pressure surface, although Correction Curve No. 1 shows in both cases a definite tendency to give values slightly too high. On the other hand, the automatic correction shows a slight "undercorrection" especially relative to the East Boston interpolations, which are generally lower than those obtained at Grenier Field.

Data for 123 observations based on automatically-corrected pressures at Mt. Washington, covering the period October 9 through December 30, 1945, are shown in Table 6. Since maps are now being drawn to show the height of the 850-millibar pressure surface rather than the pressures at the 5000-foot level, the values in Table 6 are given in terms of the number of feet discrepancy except for the means of all observations which have been converted to millibars for purposes of comparison. The Mt. Washington pressures are generally higher than the East Boston interpolated values, while they are more evenly divided, positive and negative, when compared to the Grenier Field values.

The frequency table for this set of 123 observations, Table 7, shows again that Correction Curve No. 1 tends to give values slightly too high, and that the East Boston interpolated values are generally lower than those from Grenier Field. However, Table 7 shows that the automatic correction has a tendency to give values slightly too high, whereas in the original correction-curve method (see Table 5), the tendency was toward values slightly too low. The best agreement, considering all comparisons and the total number of cases in which there was a ± one mb or less discrepancy, seems to be between Mt. Washington and the Grenier Field interpolated values while using the automatic-correction method. Inconsistencies in results between the older and newer data may be due to the fact that the earlier data were obtained while using an experimental pitot-tube assembly for the automatic correction but with a standard three-cup anemometer generally supplying the average wind velocity for use with the correction curve. For all but the first 20 of the later comparative observations, a new pitot-tube assembly was put up at a slightly better

Table 7--Frequency table showing frequency of various discrepancies in height of the 850-millibar constant-pressure surface at location of Mt. Washington (with height discrepancies converted to equivalent pressure discrepancies where the station pressure was corrected on the one hand by the use of Correction Curve No. 1, and on the other hand by the use of the pitot-tube automatic correction. Mt. Washington pressures are reduced to the 850-millibar height and compared to interpolated 850-millibar values for Mt. Washington as determined from 850-millibar maps drawn at East Boston and Grenier Field

Discrepancy	Mt. Washington minus East Boston map				Mt. Washington minus Grenier Field map				East Boston map minus Grenier Field map	
	Curve No. 1		Automatic correction		Curve No. 1		Automatic correction			
	No. of obs.	Pct of total	No. of obs.	Pct of total	No. of obs.	Pct of total	No. of obs.	Pct of total	No. of obs.	Pct of total
(to nearest mb)										
+ 8	1	1	..	..	1	1	..	..	..	..
+ 7	..	..	..	..	1	1	..	..	..	..
+ 6	1	1	..	..	..	..	..	..	..	..
+ 5	2	2	..	..	..	..	..	..	..	..
+ 4	5	4	..	..	5	4	..	..	..	..
+ 3	15	12	3	2	10	8	2	2	..	..
+ 2	24	19	15	12	30	24	3	2	5	4
+ 1	36	29	30	24	35	28	35	28	21	17
0	27	22	44	36	28	23	47	38	59	48
- 1	8	6	17	14	13	11	27	22	35	28
- 2	4	3	11	9	..	..	8	6	2	2
- 3	..	..	3	2	..	..	1	1	..	..
Total obs.	123		123		123		123		123	
Discrepancy of ± 1 mb or less		58		74		62		89		93

exposure and the wind velocities for use with the curve were thereafter deduced from the impact pressure indicated by the pitot tube. It should be significant in so far as the use of the curve is concerned that the average velocity for the later data ranged from ten to 15 mph greater than during the period of earlier data. With higher velocities, the difficulty in reading a rapidly-pumping barometer could account for larger errors in the comparisons.

Description of pitot-tube assembly and associated equipment--The newer pitot-tube assembly, installed October 22, 1945, is mounted in the center of the Observatory tower about eight feet above the parapet and 37 feet above the ground, taking the place of the no. 2 heated anemometer [SCHAEFER, 1946]. The pitot tube itself is a standard Kollsman Type D-1 in the shape of a tapered cylinder which is kept into the wind by a suitable vane, both mounted on a bearing assembly. Extending down from the bearing assembly is a collar four inches in diameter by six inches long which protects the bearing from moisture, etc. The tubes leading from the static and pressure openings of the Kollsman tube, as well as the pitot heater wire leads, pass down through the center of the bearing. Just below the bearing, water traps have been put in both static and pressure lines. In the bottom of these traps Porex plugs have been inserted and the tendency is for the water gradually to seep through the effective capillaries of the plug, thereby keeping the traps drained at all times. Any air leakage is so small as to be negligible. This adaptation of the Kollsman pitot tube to the requirements of the Mt. Washington exposure was made by Vincent J. Schaefer of the General Electric Co., Schenectady, New York.

Connected to the outlets from the traps are pieces of flexible rubber tubing about 14 inches long which connect, respectively, to two ten-foot sections of 3/16-inch I. D. aluminum tubing leading down through the length of pipe on which the pitot assembly is mounted. The lengths of rubber tubing provide the necessary flexible connection between the stationary and movable parts of the assembly and are slack enough to allow one complete revolution of the pitot tube and vane without constricting the line and without affecting the action of the vane except possibly in very low winds.

Heat can be applied to the pitot tube itself through its built-in electrical heater. During the frequent conditions of icing on Mt. Washington, heat is necessary around the collar and the upper part of the mast to allow free movement of the vane. The collar and the upper 16 inches of the mast are made up of a specially-formed combination of glass cloth saturated with a thermosetting and insulating plastic called Permafil into which is embedded nichrome heater wires. The moisture traps have similarly-constructed heater units around them to keep any collection from freezing and so prevent the desired drainage through the Porex plugs. As an added precaution, heat can be applied to the ten-foot lengths of aluminum tubing in case of moisture freezing in this part of the line.

To the lower end of the aluminum tubing, each line has coupled to it 21 feet of plastic tubing leading to the observatory instrument room and terminating in a manifold of glass tubing which provides, through glass petcocks, seven outlets from the pressure line and seven from the static line (see Fig. 2).

To proper outlets from the manifold are connected a Hays Combustion Recorder for obtaining the wind velocity record, a standard airspeed indicator (for high-velocity indications), the connection to the Bowen fixed-cistern barometer, and a connection to a special pressure-tight box containing a standard Friez microbarograph. The latter two instruments are connected to the pressure line only.

Means of correcting the barograph trace automatically--The special pressure-tight box, made by the Instrument Division of the Weather Bureau at the request of the author, is just large enough to house a standard microbarograph. The barograph sits on a base plate of 3/8-inch sheet aluminum, and, by means of a rubber gasket and 16 small bolts, a flanged, open-ended box can be set over the barograph and fastened to the base plate, making a pressure-tight enclosure for the barograph. A single opening in the bottom of the base plate provides for venting the barograph to any source of outside pressure, which, in this case, is the impact pressure of the wind directly from from the pitot tube. The barograph trace in this way is approximately corrected at all times by the impact-wind pressure. A means of obtaining a corrected pressure characteristic and amount of pressure change is thus provided for automatically. Comparative traces obtained simultaneously with the uncorrected and the corrected barographs are shown in Figure 3.

As a check on how well the automatically-corrected pressure tendencies agree with simultaneous surface tendencies, a set of data, covering the period February 19-22, 1946, which included the passage of a coastal storm and extended from the passage of the preceding ridge to passage of the following ridge, was sent to the East Boston Weather Bureau Airport Station for analysis. It was

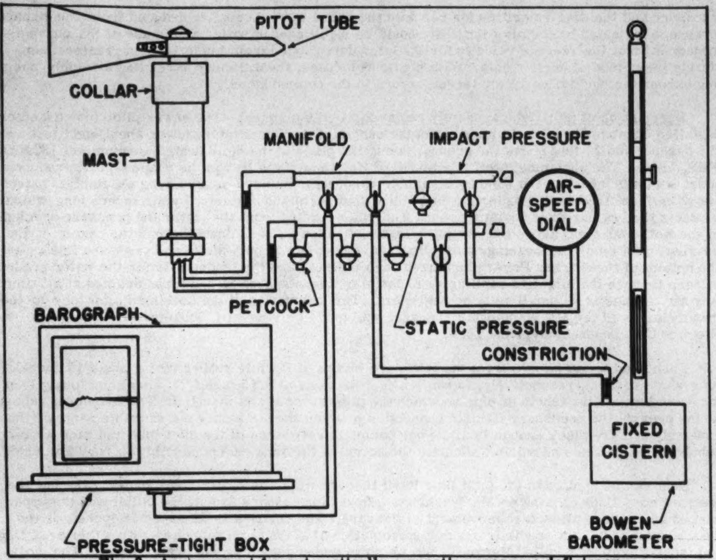
PITOT TUBE
COLLAR
MAST
MANIFOLD
IMPACT PRESSURE
AIR-SPEED DIAL
PETCOCK
STATIC PRESSURE
CONSTRICTION
BAROGRAPH
FIXED CISTERN
BOWEN BAROMETER
PRESSURE-TIGHT BOX

Fig. 2--Arrangement for automatically correcting pressure deficiency caused by wind on Mt. Washington, New Hampshire

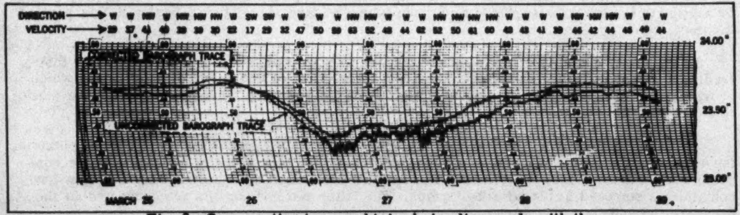

Fig. 3--Comparative traces obtained simultaneously with the uncorrected and corrected barographs

found that the uncorrected pressure tendencies had large errors, and so these were not considered further. It was also found that the corrected tendencies corresponded closely to surface tendencies but that "on passage of a ridge or trough at the surface, there is a lag of three to six hours at Mt. Washington before the tendency begins to follow the tendencies at the surface. During this time the barometer may be steady or even have a change of opposite sign. After it does start to change, the amount of change has an average value of two-thirds that of the surface change. The lag of Mt. Washington pressures fits the expected lag of troughs and ridges at upper levels." It was stated that the corrected pressure tendency, in this investigation, appeared to be a more accurate one to use.

Means of reducing "pumping" in strong gusty winds--With strong gusty winds, considerable oscillation in the indicated readings given by the recording instruments is likely. To reduce this effect, constrictions in the form of small glass capillary tubes have been put in the pressure leads, resulting in much smoother traces and easier reading of the barometer to secure a mean average value of velocity and/or pressure. The constriction giving the most satisfactory results so far has been made up of several short lengths of glass tubing (3/32-inch, I. D.) inserted in the pressure and static lines at intervals of two or three inches. Additional constrictions appear to be necessary in the line leading from the manifold to the Bowen barometer to reduce the oscillations of the mercury. Two constrictions are used, one at the manifold end of the connecting tubing and one at the barometer end, both being short lengths of 1/32-inch glass tubing. (The smaller 1/32-inch constrictions cannot be used in the line to the pressure box, as it was found to cause the barograph trace to vary slowly from an excessive positive pressure to an excessive negative pressure rather than indicating a smooth mean pressure.)

With several instruments connected to the same static and pressure lines, it was thought that interaction between them might cause erroneous readings. By cutting off, one at a time, all connections but that to the wind recorder, no appreciable change in the latter record has been noted during the several times that this experiment has been tried.

Adoption of the automatically-corrected pressure--The physical arrangement of the equipment used in this experimental work is subject to some improvement, and plans for such improvement are already in mind. On and after April 1, 1946, Mt. Washington has been authorized to use the automatic pressure-correction method in obtaining official station pressure, pressure characteristic, and amount of pressure change. Since the pitot tube in use at present is not immune from collecting moisture and ice in the lines during periods of heavy icing, there may be short periods when the automatic method becomes inoperative. During these times the Fortin barometer will be read and a new curve, Correction Curve No. 2, will be used in determining the corrected station pressure. The new Correction Curve No. 2 (see Fig. 1, and using K = 0.26 because data show it improves the results) combines the corrections necessary to overcome the lowering of pressure due to the effects of the mountain and the building (as discussed earlier). Since Curve No. 2 shows less correction to be necessary than Curve No. 1, it should give values quite comparable to those obtained by the automatic method except as previously mentioned in regard to wind direction.

Conclusion--The pitot tube-barometer arrangement described above provides a simple means of correcting approximately for the pressure deficiency caused by wind on mountain peaks, thus making pressures from mountain stations of greater practical use. A more detailed theoretical analysis of the problem has been presented by L. P. HARRISON [1946]. A study of the data obtained by using the automatic-correction method will be continued at Mt. Washington.

Although it would take some time and possibly prohibitive expense, it would seem ultimately desirable that all stations be equipped with apparatus similar to that described. First of all, excess pumping of both barometer and barograph can be reduced by merely venting the special barograph box and a Bowen barometer to the room pressure through a proper constriction in the line; secondly, and more desirably, by venting the barometer to the source of static pressure (that is, a static pressure head outside the building), the varying effects produced by wind blowing into or across openings in the structure will be eliminated; and thirdly, by choosing the proper location for the station (with topography similar to that of Mt. Washington), the barograph and barometer may be vented to the wind pressure available from the pitot tube and so compensate for the pressure deficiency due to the "mountain effect." It would also seem desirable, since the pitot tube on the vane would be used for the source of static or wind pressure, that these pressures be used to determine wind velocity and that the vaning movement be used with a contact or Selsyn recorder to indicate the wind direction. Such an arrangement ought to have definite consideration in any contemplated installation of automatic weather stations on mountain peaks.

Acknowledgments--In addition to those already mentioned, the writer is indebted to the following persons who helped in obtaining data or providing equipment: The Regional Control Officer and men of the USAAF Eighth Weather Squadron, Grenier Field, New Hampshire, for supplying data interpolated from charts at that station; the Official in Charge and other forecasters at the United States Weather Bureau Airport Station at East Boston, Massachusetts, for furnishing similar interpolated results and analyzing certain data; Irving Langmuir of the General Electric Co., Schenectady, New York, for comments and suggestions; Vincent Schaefer of General Electric Co. for supplying the manifold of glass tubing and the Hays Combustion Recorder; D. M. Little of the United States Weather Bureau and L. P. Harrison of the United States Weather Bureau Technical Investigations Section, and Charles F. Brooks of the Blue Hill Observatory for many helpful comments and suggestions; Sylvia Brooks, Sarah Wollaston, Fransisco De Costa and others of the Blue Hill staff for copying and relaying data via radio; Adam J. Eckert, formerly of the Eighth Weather Squadron attached to Mt. Washington, whose experimental work in adapting the standard pitot tube for use in indicating wind velocity on Mt. Washington led to its present use in correcting the pressure; and last, but not least, the following past and present members of the staff of the United States Weather Bureau-Mt. Washington Observatory who patiently helped in recording the pressure data at Mt. Washington: Kenneth E. Gould, Official in Charge, Marshall K. Smith and Norman E. Turner of the United States Weather Bureau; Victor F. Clark, Vernon Humphrey, Robert L. Ziriax, and Kenneth K. Larsen of the Eighth Weather Squadron, and Philip C. Betler, Mt. Washington Observatory physicist.

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DISCUSSION

F. A. Brooks (University of California, at Davis, California)--There seems to be some disagreement between Falconer's general interpretation of velocity-head correction and that in the analytical treatment of the same problem by L. P. Harrison [see "References" at end of discussion, HARRISON, 1946]. It seems to me that a clearer concept of the phenomenon of mountain-pressure deviation is possible through the simple analogy of wind-tunnel air flow around obstacles, since in this case the complicated effects of height, density, and thermodynamics are avoided, but the basic fluid-dynamic relations still obtain.

Clearly, Falconer has developed a good means for automatic correction of barometric pressure observed on mountain tops. Since the pressure correction is necessary only because of wind dynamics, the correction should certainly be proportional to the square of the wind velocity. It seems to me, however, that: "Approximate equivalence" with $\rho V_{37\ \mathrm{ft}}{}^2/2$ is purely fortuitous, and that on another mountain top it might be twice or half or any proportion to observed velocity head.

There may be some misinterpretation of the phrase ". . . resulting in a pressure indicated by the barometer approximately equal to the pressure that would exist if the mountain were not there." Literally this infers that there is no wind except near the mountain. The treatment would be clearer by making full use of Bernoulli's concept of constant total head (assuming a mountain of exactly 5000-foot height): $P_{5000\ \mathrm{ft\ free}} + \rho V^2_{\mathrm{gradient\ w}}/2 = P_{5000\ \mathrm{ft\ mtn.}} + \rho V^2_{\mathrm{over\text{-}mtn.\ wind}}/2$

The left-hand side of this equation is the reading of an impact tube at 5000 feet in the gradient wind. The first term is the barometric pressure, and the second is the velocity head of the gradient wind which is disregarded in usual meteorological practice, because we live in the air stream. The correction difference between observed mountain pressure and 5000-foot pressure is then: $P_{5000\ \mathrm{ft\ mtn}} - P_{5000\ \mathrm{ft\ free}} = \rho(V^2_{\mathrm{over\text{-}mtn}} - V^2_{\mathrm{gradient}})/2$. The observed $V^2{}_{37\ \mathrm{ft}}$ at Mt. Washington evidently matches the $(V^2_{\mathrm{over\text{-}mtn}} - V^2_{\mathrm{gradient}})$.

The narrowing of stream-flow ribbons for two-dimensional, frictionless air flow over an obstruction is fixed geometrically, and consequently the superspeed in the narrowed portions is directly proportional to the free-stream velocity, namely: $V_{\mathrm{over\text{-}mtn}} = CV_{\mathrm{gradient}}$ and $(V^2_{\mathrm{over\text{-}mtn}} - V^2_{\mathrm{gradient}}) = V^2_{\mathrm{gradient}}(C^2 - 1) = V^2_{37\ \mathrm{ft\ \ Mt.\ W.}}$

If the effective superspeed happens to be 1.414 times the gradient wind, the velocity observed 37 feet above Mt. Washington would be the same as the gradient wind. If this suits the observed conditions, it indicates that the frictional layer is deeper than 37 feet. In wind-tunnel interpretation, the surface pressure is considered to extend unchanged up through the frictional layer to the Bernoulli stream flow. Above the frictional layer the pressure over the mountain would approach barometric as the narrowing of the stream ribbons fades out to uniform straight flow. A good treatment of conformal transformation of two-dimensional potential stream-function flow over a transverse cylinder is given by MILNE-THOMPSON [1938].

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MILNE-THOMSON, Theoretical hydrodynamics, Macmillan, London, 1938.

L. P. Harrison (U. S. Weather Bureau, Washington, D. C.)--Falconer's justification of the use of a pitot tube to compensate for the pressure deficiency produced by the wind on Mt. Washington is predicated wholly on empirical grounds. The experimental results only apply to specific locations of the barometer, pitot tube, and anemometer. For other locations it is doubtless true that different relationships than those found in the case of Mt. Washington would obtain.

In order to secure a comprehensive analytical treatment of the problem based on actual atmospheric conditions, it is necessary to take into account the amount of lift which the air experiences in flowing over the mountain and the distribution of wind velocity around and over the mountain. These factors determine the calculation of the total energy head in the stream tube flowing by the anemometer. Since the primary object is to relate pressure as observed on the summit to free-air pressure at the same level, thermodynamical aspects enter the problem, considering that the atmosphere is compressible and density changes occur owing to adiabatic lifting and condensation of water vapor as the pertinent stream tube suffers an increase in elevation on passing from free air to summit. An effort has been made to take these factors into account in my treatment of the problem on an analytical basis.

With reference to C and K in equations (2) and (5), one may agree that these so-called constants are valid under more or less average conditions, provided the values of C and K are deduced from the mean of many observations. However, on individual occasions, certain meteorological factors may cause the pertinent values of C and K to deviate from the mean values adopted (1.46 and 0.3, respectively). Meteorological factors which may produce such deviations are the wind, temperature, and moisture distributions in the vicinity of the station. This brings into question the possible variations in (C - K) relative to unity (1), for it is on the equality of (C - K) with unity that the use of the pitot tube to compensate for the pressure deficiency, ΔP_m, is justified.

More specifically, if the appropriate value of ΔP_m under given meteorological conditions is unequal to $\rho V^2/2$, then the pitot tube does not supply a pressure increment which will correct the observed barometer reading by the requisite amount to secure a pressure representative of the free air locally.

One may expect, on the basis of experience and dynamical theory, that deviations from the assumed equality of ΔP_m and $\rho V^2/2$ do occur. The goodness of the agreement between these quantities in individual cases can only be determined empirically. Naturally, the relation between them depends upon the elevation at which V, the wind velocity just above the summit of the mountain, is measured. Even if ΔP_m were equal to $\rho V^2/2$ for a given mountain and for some definite elevation above summit at which V is measured, then it would not follow that at other mountains and elevations the same results would be found.

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EQUIPMENT FOR RADIO REPORTING OF WIND SPEED AND DIRECTION

Ronald L. Ives

Abstract--A modulator control device for radio reporting of wind speed and direction, as measured by standard instruments, is here outlined.

Introduction--In several types of meteorological research an instrument is needed to report wind speed and direction by radio, either continuously or at intervals determined by a clock or other control.

Field conditions require that the equipment be simple, rugged, and economical of battery power. It is desirable that the wind data be transmitted simultaneously with other meteorological information so that the number of radio channels required and the amount of field equipment will be a minimum.

Modulator control

Equipment for modulating the radio transmissions in accord with the position of the wind vane and the rate of contact closure of the anemometer consists of the instruments, a stepping switch operated by the anemometer, and operating adjuncts.

Circuit and operation--The circuit of one form of the wind-operated modulator control is shown in Figure 1. Numerous alternative circuits, operating on the same general principles, are possible.

The anemometer relay (left relay, see Fig. 1) operates at each closure of the anemometer contacts, and in turn operates the limiter relay (right relay, see Fig. 1). This arrangement energizes the stepping switch coil through the lower contacts of the limiter relay for a finite short interval (such as 0.1 sec) regardless of the duration of the anemometer contact closure, and closes the modulator circuit for the same length of time [see "References" at end of paper, IVES, 1946 b]. (Working constants for a 6-volt battery are: Relay resistance, 50 ohms, C2, 1000 MF; R2, 3 ohms.)

The arm of the stepping switch advances one position for each energization of the coil and hence, as the coil is anemometer controlled, one position for each anemometer contact closure.

The stepping switch contacts are wired to the wind vane contacts in any desired sequence, but are so connected that the modulator circuit is continuously closed for one anemometer interval when the switch arm contacts the position corresponding to the wind source. Any desired arrangement can be used to indicate the start of a direction sequence. One such circuit is shown in Figure 1. To keep record interpretation time within reasonable limits, it is best to use a relatively simple contact arrangement.

Power supply--In a preliminary model of this modulator control, the stepping switch was operated from the filament battery of the transmitter, and unwanted modulation was secured because the tube filaments dimmed each time the stepping circuit was closed, and the limiter "acted up" because of voltage fluctuations. As the pull-in current of a stepping switch greatly exceeds the holding current, but need only be drawn for a small fraction of a second (such as 0.05), a condenser-resistor circuit, consisting of C1 and R1 (see Fig. 1), was installed to "depeak" the battery drains. With this circuit, the initial pull-in current is drawn from the condenser C1, and the holding current from the battery through R1, whose value is determined by the characteristics of the stepping switch coil. When the stepping circuit is open, C1 recharges from the battery through R1, at a rate indicated by (1).

$$T = 2.303R_1C_1 \log_{10}(Eb/Eh) \tag{1}$$

in which T = time, in seconds, to recharge condenser to full battery voltage, R_1 = resistance of battery circuit (ohms), C_1 = capacity of condenser (farads), Eb = battery voltage (no load volts), and Eh = holding voltage of stepping coil. This arrangement, besides eliminating conflict of

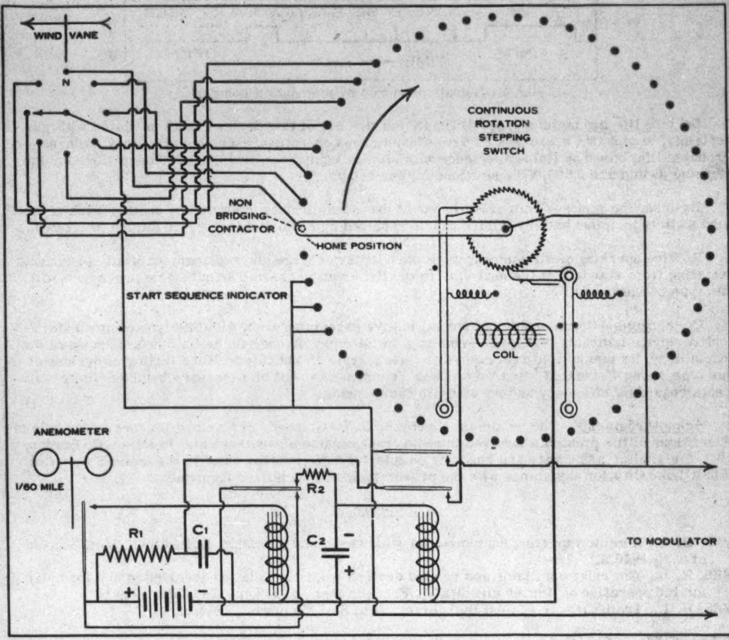

Fig. 1--Circuit of modulator control

electrical functions, permits the use of a filament battery of high initial internal resistance, such as a dry cell, and extends the useful life of the battery appreciably.

Modulation--This modulator control was used with several types of modulation and performed satisfactorily with all standard types. It was also used to insert and remove a small condenser in the tank circuit of the oscillator to produce "carrier shift" modulation. Within reasonable limits, this "carrier shift" modulation can be used in addition to other modulation systems and is detected by use of a sharply-tuned circuit in the receiver, which in turn operates a relay.

Another form of modulation, here called "power modulation" was also used successfully. In this system, the modulator inserts and removes a resistor in the plate supply of the oscillator, which modifies the power radiated by the system. This was detected by a modified field strength meter and relay in the receiver. This, also, can be used in a system having one or more other modulations.

One transmitter, which worked experimentally but required a somewhat complex receiver, employed carrier shift modulation to indicate barometric pressure, power modulation for the wind data, and conventional amplitude modulation at audible frequencies for the temperature and humidity data, with the indexing frequencies switched in by the wind indicator stepping switch.

Signals and interpretation--Signals recorded on tape by this transmitter are shown in Figure 2. The contacting arrangement producing these signals is that shown in Figure 1, with the wind vane at West position. Wind speed is found by comparing the space between signals with the paper speed, and then computing the speed in desired units by use of the anemometer contact interval. Details of this type of interpretation, and various mechanical aids therefor, are described elsewhere [IVES, 1946 a].

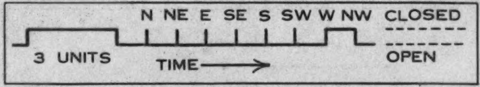

Fig. 2--Signals produced by modulation control

Service life and maintenance--Ultimate service life of this device cannot be stated with any certainty, except that it exceeds 30 days of continuous operation, exclusive of battery failures. Probable life, based on field experience with similar equipment, is 10,000,000 operations for the stepping switch and 2,500,000 operations for the relays.

By inserting a close-limit relay in one of the index circuits, operated by another bank of the wind switch, incipient battery failure can be reported by radio and in-service failure prevented.

Routine checking of all components at each battery change and replacement of all components deviating from standard at the next visit to the field stations seems an advisable procedure with this type of equipment.

Conclusions--Considerable but not exhaustive experimentation with this type of modulator control device indicates that it performs in a satisfactory manner in the field and, because of its adaptability, its use in field researches of certain types is indicated. More testing of devices of this type, using "standard" instead of "war" components, will be necessary before definite statements regarding efficiency and service life can be made.

Acknowledgments--The writer is indebted to S. W. Grinnell, of Stanford University for helpful discussions of the problems involved in radio transmission of weather data; to Milton C. Berdan, CWS, for similar assistance and checking on interference problems; and to the Radio Supply Co., of Salt Lake City for assistance with the procurement of specialized components.

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SOME ASPECTS OF PUERTO RICAN RAINFALL

Herbert Riehl and Elmer Schacht

Abstract--Rainfall in Puerto Rico during the dry season (roughly December to April) varies markedly from year to year. In preliminary studies directed toward development of seasonal forecasting methods, the precipitation records have been analyzed to determine the synoptic types favorable for different seasonal rainfall totals during the months January to March, inclusive. Synoptic studies indicate that days with 0.25 inch or more of rainfall are usually the result of major synoptic disturbances, and that days with 0.20 or less represent undisturbed atmospheric flow with frequent light showers. An analysis of over 40 years of record on this basis shows that most of the heavier precipitation of the dry season is accounted for by major synoptic disturbances. Seasons of deficient rainfall tend to have a high frequency of days with 0.20 inch or less of precipitation; this correlation is appreciably greater than with the number of days having no rainfall.

The data presented here are principally for San Juan on the north coast and Mayagüez on the west coast. Results obtained for both stations are in agreement, but correlation of rainfall between the two stations is not very good, indicating that, for forecast purposes, the effects of the broad-scale circulation patterns must be correlated separately for different stations or areas.

The usefulness of seasonal precipitation forecasts has long been evident in many parts of the tropics. Many attempts have been made, notably by the Indian meteorologists, to find suitable methods for the preparation of these forecasts. For Puerto Rico, such predictions would also be of great benefit, especially during the winter dry season.

This statement may seem surprising, as the climate of Puerto Rico is often classified as "humid tropical" or "humid subtropical," with some precipitation recorded in every month of the year. While this is true in general, those who have lived in Puerto Rico know that droughts so severe may occur during the dry season that it becomes necessary to curtail the water and electric power consumption in the cities, and that the livestock in the mountains has to be driven for many miles to the few springs and brooks that have not dried out completely.

The considerable frequency of drought during the dry season, and the corresponding occurrence of excessive precipitation, may be verified statistically by reference to the large network of rainfall stations on the island. These have been maintained by the United States Weather Bureau at many locations for over 40 years. As representative samples of the calculations made, the figures of San Juan and Mayagüez will be used primarily. The meteorological conditions at these two stations are widely different because of their respective positions with regard to the prevailing flow of air and the mountainous interior of Puerto Rico (see Fig. 1). At San Juan the sea breeze intensifies the Trade Wind, while the sea breeze opposes the Trade at Maygüez. In addition, all winds at Mayagüez with an easterly component blow from the mountains downward toward the coast.

Throughout the potential drought period, roughly from December to April, the variation of the observed rainfall from year to year is very great. For instance, in February, in the middle of the dry season, the average rainfall at San Juan for 43 years is 2.69 inches. The mean aperiodic interannual rainfall variation (mean difference in precipitation total for that month from one year to the next) for this month is 2.15 inches or 80 per cent of the mean rainfall. At Mayagüez, the average precipitation for February is 2.09 inches, also on the basis of a 43-year record. This figure itself indicates conditions bordering on drought. The mean aperiodic variation is 2.06 inches, or 98 per cent of the average rainfall. As commonly noted in the tropics, the aperiodic change is greatest in the months with the smallest average precipitation, and it decreases as the rainfall increases.

Figure 2 contains the frequency distribution of the rainfall deviations from the mean for February, expressed in per cent of the average. For comparison, the curve for Caguas, located in a gap in the mountainous interior about 20 miles south of San Juan, has also been included. Figure 2 shows how infrequently rainfall near the mean is recorded in individual years, and that

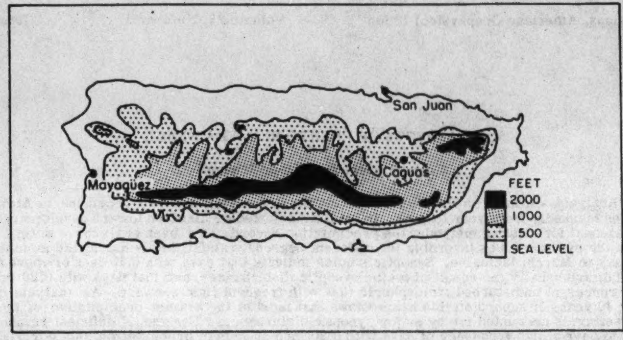
San Juan
Caguas
Mayagüez
FEET
2000
1000
500
SEA LEVEL

Fig. 1--Topographic outline of Puerto Rico (located about 18°N, 66°W). The length of the island is approximately 100 miles and the width 40 miles

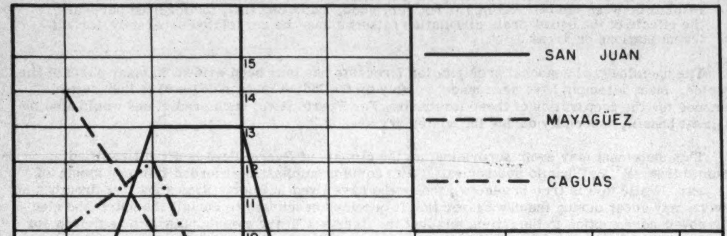

Fig. 2--Frequency distribution of the rainfall deviations from the mean for February at San Juan, Mayagüez, and Caguas. Deviations in per cent of the average (abscissa); number of occurrences for each class interval of the deviations (ordinate)

large deviations are the rule rather than the exception, particularly at Caguas and Mayagüez. The negative deviations exceed the positive deviations at all three stations, showing the effect of a few years with excessive rainfall on the mean. Therefore, the mean can hardly be considered as a normal, as was also shown in a recent report on Hawaiian rainfall by LANDSBERG [see "References" at end of paper, in press].

The preceding figures suggest a need for extended rainfall predictions for Puerto Rico. As is well known, however, it is extremely difficult to find a satisfactory basis for an approach to the problem of making such forecasts, especially in many parts of the tropics where the correlation between the deviations of pressure and rainfall from the average often is very small. At San Juan no significant relation could be found. As an initial step in the analysis of the causes for deficient or excessive rainfall during winter an attempt was made to determine to what extent the rainfall figures themselves supply information, an approach first suggested by Chas. S. Gilman of the United States Weather Bureau.

The rainfall of Puerto Rico may be divided broadly into local showers and precipitation connected with major synoptic disturbances during winter, as described elsewhere [RIEHL, 1945]. During the winters 1943-46, when regular daily weather analyses with the aid of upper-air data were carried out, it became clear that the intensity, frequency, and average position of the atmospheric disturbances varied greatly from one winter to the next. Moreover, the general circulation at times appeared to be favorable for the occurrence of many days with showery activities of a local character, not caused by cyclonic disturbances of the general flow pattern, while during other months this type of rainfall was completely suppressed. The question arises as to whether a lack of pronounced synoptic disturbances or a cessation of the local showers is mainly responsible for rainfall deficits; and whether rainfall excess is due to an increased frequency of synoptic systems or isolated days with extreme precipitation. It was therefore attempted to determine the average frequency of days with cyclonic and with local precipitation during the dry season and to correlate the deviations from the mean of these two types of days with the deviations of the rainfall from the mean.

It has been the experience during the analysis 1943-46 that precipitation in excess of 0.25 inch in 24 hours during the dry season usually will take place only in connection with a marked disturbance, except near the higher mountain ranges. Local showers and precipitation associated with weak, especially dissipating, disturbances account for the smaller amounts. The occurrence of precipitation in excess of 0.25 inch therefore was taken as an indication of the presence of a pronounced disturbance. This amount is somewhat subjective and can serve only as a first approximation. It was not possible to verify its validity because of lack of a network of adequate upper-air data prior to 1943. Sea-level charts alone are insufficient for this purpose.

The frequency of days with cyclonic precipitation and of days with local showers was obtained from the files of the United States Weather Bureau, which contain the precipitation amount for each 24-hour interval. Days with less than 0.20 inch were considered as representative of undisturbed flow, while the small borderline group from 0.20 to 0.25 inch was excluded. Very few cases fell into this class. The use of the daily precipitation figures contains an unavoidable source of error: Rainfall connected with a major perturbation may start during the evening of one day and continue past midnight. The total precipitation because of this disturbance then would be distributed on the records over two days, and the rainfall on one or both of these days may fall short of the 0.25 value. It is likely, however, that the frequency of such cases is too small to make the figures for the whole 43-year period unrepresentative. Another unavoidable source of error is the showery and often spotty character of the precipitation, which at times leads to unrepresentative rainfall values at individual gages. This difficulty has been stressed frequently in the literature.

The correlation of the deviations from the average of the number of days with rainfall greater than 0.25 inch and less than 0.20 inch against the deviations of the rainfall from the mean for the corresponding month was carried out for each month from December to April. Eight stations were used, located in different parts of the island, for which the synoptic interpretation of the rainfall data as given above appeared reasonable. Additional subdivisions of the daily rainfall amounts, such as days with no precipitation, days with less than 0.10 inch and greater than 0.50 inch, were also made. As the results of all stations irrespective of location unexpectedly showed a fairly homogeneous picture, only those for San Juan and Mayagüez will be presented here.

The deviations of the rainfall from the mean for individual months are most significant for a study of drought, if the persistence of the rainfall deviations throughout the dry season is high. Such persistence was not found in Puerto Rico. It was preferable, therefore, to extend the correlations also over the principal part of the dry season, January to March, inclusive, and compare the results with those of the individual months. The figures were quite homogeneous, both as regards the comparison of January, February, and March with each other and with the figures for the whole dry season. In fact, the correlations were somewhat more pronounced when the whole period January to March was considered.

Figures 3 and 4 are scatter diagrams showing samples of the correlations for San Juan and Mayagüez for the period January to March. The deviation from the mean of the number of days with rainfall greater than 0.25 inch has been plotted against the deviation of the rainfall from the mean for each dry season for the 43-year period at San Juan (see Fig. 3) and Mayagüez (see Fig. 4). The mean rainfall for January to March is 9.88 inches at San Juan and 7.98 inches at Mayagüez. The average number of days with rainfall greater than 0.25 inch for the 90-day period is 10.9 days at San Juan and 9.4 days at Mayagüez. To make Figures 3 and 4 readily comparable, all deviations have been plotted in per cent of the means. The correlation coefficient at San Juan is + 0.71, and at Mayagüez + 0.91.

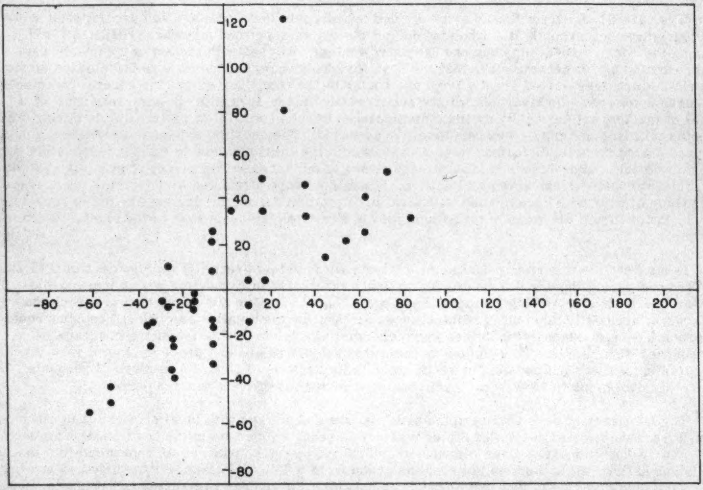

Fig. 3--Scatter diagram, January to March, at San Juan, of the deviations of the rainfall from the average, in per cent of the average (ordinate), and the deviations of the number of days with precipitation greater than 0.25 inch per day, in per cent of the average (abscissa)

Since, as previously assumed, rainfall in excess of 0.25 inch per day is taken as indicative of the presence of a pronounced disturbance, Figures 3 and 4 demonstrate clearly that the dry-season precipitation over Puerto Rico is dependent on the major disturbances that pass over the island during winter. Precipitation above average predominantly is not the result of isolated days with excessive rainfall. The larger the positive deviation of the rainfall from the average becomes, the greater is the frequency of days under the influence of upper-air troughs and shearlines. This increased frequency may be caused by the stagnation of one trough over the area, or by the rapid passage of several successive disturbances. Conversely, drought occurs in years with subnormal activity of upper troughs. Increased local shower activity does not appear as a balancing factor.

In consequence, the deviations from the mean of the number of days with rainfall less than 0.20 inch correlated against the deviations of the rainfall from the mean, is negative (correlation coefficient at San Juan - 0.70, at Mayagüez - 0.91). This may simply be interpreted as an indication that when the rainfall is heavy there are few dry days, and that with light rainfall the number of dry days is large. However, if the deviations of the rainfall from the mean are correlated against the deviations from average of the number of days without any precipitation, the resulting coeffi-

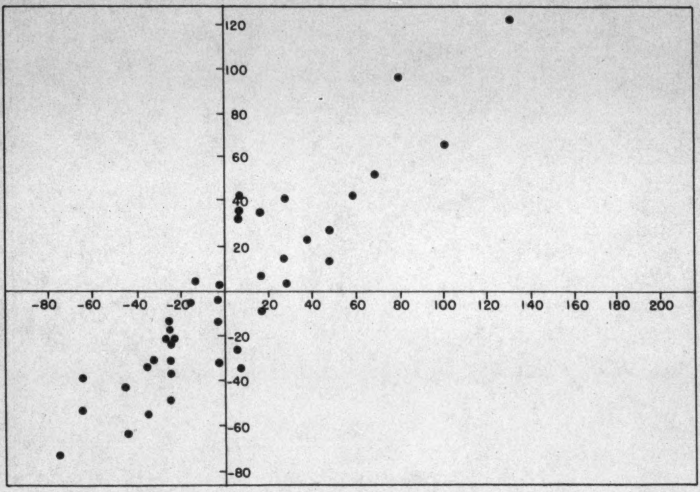

Fig. 4--Scatter diagram, January to March, at Mayagüez, of the deviations of the rainfall from the average, in per cent of the average (ordinate), and the deviations of the number of days with precipitation greater than 0.25 inch per day, in per cent of the average (abscissa)

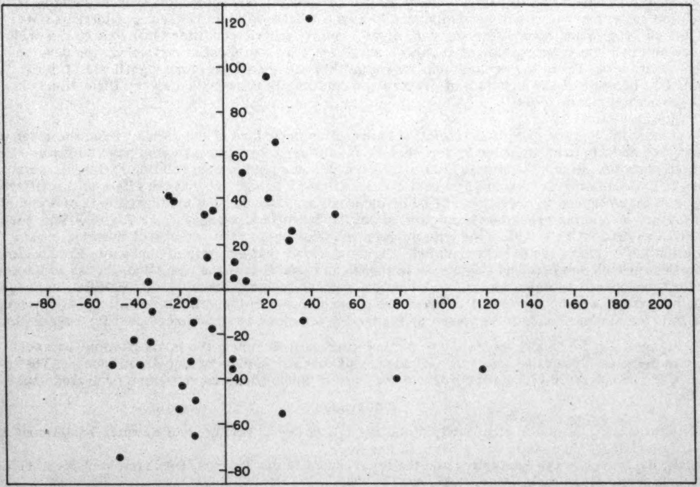

Fig. 5--Scatter diagram, January to March, of the deviations of the rainfall from the average at Mayagüez, in per cent of the average (ordinate), and the same quantity for San Juan (abscissa)

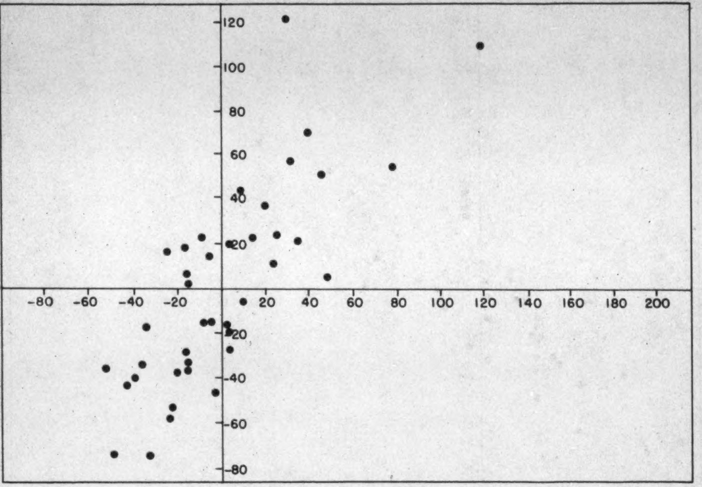

Fig. 6--Scatter diagram, January to March, of the deviations of the rainfall from the average at Caguas, in per cent of the average (ordinate), and the same quantity for San Juan (abscissa)

cients are considerably smaller than those obtained by using all days with precipitation less than 0.20 inch (coefficient at San Juan - 0.47, at Mayagüez - 0.50). This indicates that in months with cyclonic activity greater than normal, there is also a relatively high frequency of intermediate days with pronounced subsidence and very clear skies. Synoptic conditions that lead to the occurrence of a prolonged succession of days with small showers are most favorable for the development of drought. From the agricultural viewpoint this becomes even more significant if it is noted that because of the high rate of evaporation small daily showers have very little effect on the ground moisture.

It remains to ascertain the correlation between the departure of the rainfall from the mean at Mayagüez and San Juan, in order to see whether the different synoptic systems have the same effect at both stations. Figure 5 gives the result. Although some positive correlation exists, its smallness is disappointing in view of Figures 3 and 4. Figure 5 brings out that the effect of the different synoptic disturbances is greatly modified by local factors, and that the modification is of a complex character. A similar check has been carried out for San Juan and Caguas (see Fig. 6). The correlation coefficient is + 0.79, a very high figure considering that the records of two single rain gages in the tropics have been correlated. Figure 6 shows that synoptic disturbances have a similar effect at both San Juan and Caguas, even though San Juan lies at the coast and Caguas in the interior, surrounded by mountains. As also noted on other tropical islands [LANDSBERG, in press], it is by no means to be expected that an inverse course between the rainfall deviations at coastal and interior stations exists. As shown by Figure 6, there may be pronounced positive correlations.

Figures 5 and 6 finally indicate that further correlations among the island stations are necessary to delineate areas that react in a homogeneous manner to the synoptic disturbances. The effect of the broad-scale circulation patterns for each of these areas must then be evaluated separately.

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PERIOD INCREASE OF OCEAN SWELL

H. U. Sverdrup

(Contribution from the Scripps Institution of Oceanography, New Series, no. 305. This work represents results of research carried out for the Hydrographic Office and the Bureau of Ships of the Navy Department under contract with the University of California.)

Abstract--It can be considered well established that the observed periods of ocean swell are longer than the observed periods of the waves in the generating area. More recently it has been demonstrated that a wave spectrum is always present and that observed periods refer to the periods of the highest waves in the spectrum, the waves of maximum energy. These are called the significant waves. Furthermore, Munk has shown that at least the forerunners of swell have the character of impulsively generated waves in deep water which advance as conservative waves.

Assuming that swell generally has these characteristics, it is shown that the air resistance which the swell encounters leads to a selective dissipation. The energy associated with the shorter period waves is dissipated more rapidly than that of the longer period waves, and consequently the energy maximum shifts toward longer periods, that is, the period of the significant waves increases. The effect is modified by following or opposing winds. Numerical examples are in satisfactory agreement with results from the semi-empirical graphs of Sverdrup and Munk.

The energy considerations indicate numerous new possibilities for the interpretation of records of swell, and it is hoped that these suggestions will further stimulate the effort to establish well located swell-recording stations and to develop instruments for rapid analysis of wave records that give complete information as to the wave spectrum.

Introduction

After decades of discussion, it is now generally agreed that the observed periods of swell from a distant source are longer than the periods of the waves in the source region, the generating area. So far, no satisfactory explanation has been offered for this period increase. When SVERDRUP and MUNK [see "References" at end of paper, 1946] established relationships which, on the one hand, served forecasting purposes and, on the other hand, gave a framework into which observed values could be fitted, their approach was not intended as an examination of the processes which explain the observed period increase.

Before attempting any explanation it is necessary to specify what is meant by "observed periods." Detailed records of waves in the generating area [EHRING, 1940] and of swell [MUNK, 1947a] have demonstrated that not only the waves in the generating area are extremely complicated but swell is also complex, even though it may appear quite regular. In the case of swell this complexity has been brought out by the analysis of wave records obtained at Pendeen, England, by the British Admiralty Wave Research Group and at Cuttyhunk, Massachusetts, by the Woods Hole Oceanographic Institution. These analyses demonstrate that during a 20- to 30-minute interval the swell is composed of waves of widely different periods.

In Figure 1, which shows an analysis of a record of swell at Pendeen, England [BARBER, URSELL, DARBYSHIRE, and TUCKER, 1946], the wave periods are entered along the abscissa and the ordinate gives an approximate measure of the heights of the waves and the frequency with which waves of different periods occur. Thus, in the example, the predominant waves had periods between 13 and 15 seconds, but waves of periods ranging from 10 to 24 seconds were also recorded. Under such conditions an observer would visually recognize only the high waves of periods 13 to 15 seconds because these would mask all lower waves of shorter or longer periods. In order to characterize the higher waves the term "significant waves" has been introduced [SVERDRUP and MUNK, 1946] to refer to "waves having the average height and period of the highest one-third of the waves."

Experience gained so far indicates that the concept of significant waves is very useful and

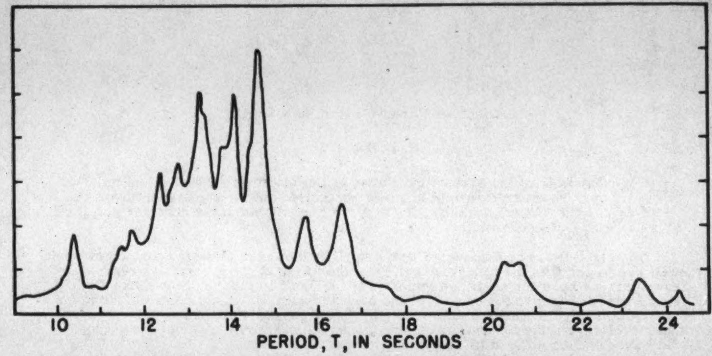

Fig. 1--Spectrogram of ocean swell recorded at Pendeen, England

that independent observers arrive at nearly the same values for wave height and wave period if, during a time interval of 10 to 20 minutes, they record only the highest two or three waves in every group. Since these are most readily recognized, it seems probable that earlier observations all refer to the higher waves present and that, in general, "observed waves" represent approximately the significant waves as defined above. Therefore, the empirical evidence as to period increase is best stated by saying that the period of the significant waves increases. This increase is quite unrelated to the period increase of individual waves which has been discussed by MUNK [1947a].

The realization of the general existence of a period spectrum with maximum wave heights (significant waves) somewhere in the spectrum places the problem of period increase in an entirely different light. An increase in the period of the significant waves implies now that with increasing travel time the region of maximum wave height shifts toward longer wave periods, that is, towards lower frequencies. The occurrence of a shift of this nature indicates that the advancing swell is subject to a selective attenuation by which the energy of the higher frequencies (the shorter periods) is more rapidly dissipated than that of the lower frequencies. It will be shown here, first, that a period spectrum can be expected to be present in the generating area if the waves can be considered as being impulsively generated and, second, that the air resistance which the advancing swell meets is selective and must lead to an increase of period of the significant waves.

Kinematics of surface waves in deep water

Conservative waves--Wave motion is called conservative in a region AB if in a time interval, $t \gg T$, no crests are generated or destroyed (ROSSBY, 1945; MUNK, 1947b). This condition can be written

$$\partial(1/L)/\partial t + \partial(1/T)/\partial x = 0 \qquad (1)$$

where L is wave length and T is wave period. The wave velocity C, which will be referred to as phase velocity, is by definition equal to L/T, and in deep water, according to the classical theory,

$$C = (g/2\pi)T \qquad L = (g/2\pi)T^2 \qquad (2)$$

By means of (2), equation (1) takes the form

$$\partial T/\partial t + (C/2)\partial T/\partial x = 0 \qquad (3)$$

Using the symbol d/dt for the time rate of change when traveling with velocity C/2, it follows that

$$dT/dt = \partial T/\partial t + (C/2)\partial T/\partial x = 0 \qquad (4)$$

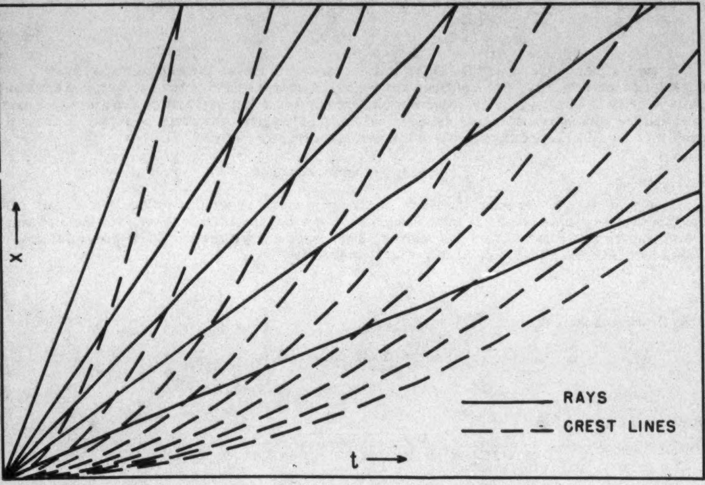

Fig. 2--Rays and crest-lines of surface waves in deep water, represented in a t-x diagram

The velocity C/2 represents the group velocity of surface waves in deep water. Equations (3) and (4) are also valid if a general symbol for group velocity is introduced.

Impulsively generated waves--An initial displacement of the free surface which at $t = 0$ is confined to the immediate neighborhood of $x = 0$ will produce a wave train which, at a distance x that is small compared to gt^2, is characterized by a slow decrease in the time interval between passages of successive wave crests. In the Cauchy-Poisson wave problem [LAMB, 1932, pp. 384-489] this interval, T, is

$$T = (4\pi/g)(x/t) \qquad (5)$$

where g is the acceleration of gravity. This value of T can be considered generally valid when dealing with centered impulsively generated conservative waves in deep water. It represents the observed period of the passing waves.

According to (5), lines of constant period (T = constant) are straight lines through the origin in a diagram with t and x as coordinates (see Fig. 2). These lines are called rays. The path of an observer who travels with a constant group velocity,

$$C/2 = (g/4\pi)T = x/t = \text{constant}$$

is represented by a ray in the t-x diagram. Such an observer will record that wave period and wave length in his neighborhood remain constant. He will also record that he is continuously being overtaken by individual waves which travel at twice his own speed.

Let the notation D/Dt indicate the time rate of change of an individual wave. Then, using (4) and (5)

$$DT/Dt = \partial T/\partial t + C(\partial T/\partial x) = -\partial T/\partial t = T/t \qquad (6)$$

By integration,

$$T/T_n = t/t_n \qquad (7)$$

where the T_n indicates the period at the time t_n. By means of (5) one obtains

$$t = t_n \sqrt{x/x_n} \qquad (8)$$

In the t-x plane, equations (7) and (8) define a family of curves through points t_n, x_n at which T has the value T_n. Each of these curves represents the path of an observer who travels at phase velocity $C = 2x/t$. Such an observer starting out on a crest will always remain on the same crest and the curves are therefore called crest lines. They are also shown in Figure 2, from which it is seen that along the crest line the period increases continuously.

Energy considerations

General equations--Assume that no wave energy is added or dissipated locally. On this assumption the local time change in wave energy E must equal the difference between the amounts of wave energy that enter and leave a volume. Since wave energy advances with group velocity it follows that [ROSSBY, 1945; SVERDRUP and MUNK, 1946]

$$\partial E/\partial t + \partial(CE/2)/\partial x = 0 \qquad (9)$$

Using the relationships

$$\partial E/\partial t = dE/dt - (C/2)\partial E/\partial x \qquad (10)$$

$$\partial(CE/2)/\partial x = (E/2)\partial C/\partial x + (C/2)\partial E/\partial x$$

and, from (2), (3), and (6),

$$(1/2)\partial C/\partial x = - (1/C)\partial C/\partial t = - (1/T)\partial T/\partial t = 1/t$$

one obtains by substitutions into (9)

$$(1/E)dE/dt = - 1/t \qquad (11)$$

In equations (4) and (9) a general symbol V could have been introduced for the group velocity instead of C/2, and one would have obtained the general equation

$$(1/E)dE/dt + \partial V/\partial x = 0 \qquad (12)$$

of which (11) is a special form applicable to surface waves in deep water.

The use of equation (10) implies that we examine the change in energy which will be recorded by an observer who travels with group velocity. By integrating (11)

$$E/E_1 = t_1/t = x_1/x \qquad (13a)$$

For deep-water waves of small steepness, E is proportional to the square of the wave height H. Therefore

$$H/H_1 = \sqrt{t_1/t} = \sqrt{x_1/x} \qquad (13b)$$

Thus, along any given ray, the wave height is proportional to the square root of the ratio between travel times or travel distance, but generally the factor of proportionality varies from ray to ray.

Application to wave spectrum--Assume that numerous wave trains are generated by a series of disturbances at x = 0, starting at t = 0 and continuing for a long time. Assume, furthermore, that waves from these disturbances arrive at $x = x_1$, $(x_1 << gt^2)$, with heights depending upon their period as indicated in Figure 3, that is, that the wave heights are small for short periods, increase to a maximum at an intermediate period, and decrease more slowly at longer periods. This is equivalent to assuming that at $x = x_1$ and at a time $t = t_1$, where t_1 is the travel time of shortest waves from x = 0 to $x = x_1$

$$\left.\begin{aligned} &H = H(T) \\ &dH/dT = 0 \text{ for } T = T_m \\ &H \to 0 \text{ as } T \to 0, \text{ and } H \to 0 \text{ as } T \to \infty \end{aligned}\right\} \qquad (14)$$

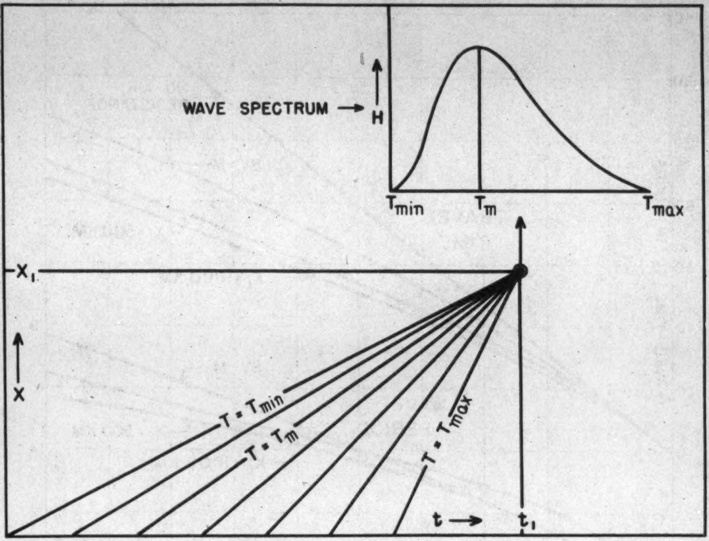

Fig. 3--Wave spectrum at $x = x_1$, $t = t_1$ as a result of numerous wave trains emitted from $x = 0$ in the time interval between $t = 0$ and $t = t_1$

These relationships between H and T represent approximately the average conditions that exist at the end of a fetch where waves raised by wind are present. At a given instant the wave pattern must probably be considered as consisting of a limited number of distinct waves, but over a time interval of one or more hours conditions of (14) may be approximately satisfied [EHRING, 1940]. The waves can probably be considered as being impulsively generated, but they may not have traveled the same distance before they arrived at the end of the fetch. Still, it is of interest to examine the conclusions which on this basis can be drawn as to the character of the swell emanating from the fetch and to compare these conclusions with empirical evidence.

The graph prepared by SVERDRUP and MUNK [1946] for forecasting swell appears to be fairly consistent with observations, and for present purposes of comparison is considered to represent observational data. A comparison between the contents of this graph and the preceding theory reveals, however, the following discrepancies, as shown in Figure 4: (a) The computed decrease in wave height is much smaller than observed; (b) the period of the highest waves remains constant, whereas observations indicate that this period increases; and (c) the travel time of the highest swell is obtained from the constant group velocity of the highest waves at the end of fetch but is much longer than indicated by the observations.

Effect of air resistance on waves traveling through regions of calm--The listed discrepancies can be eliminated to a great extent by taking into account the air resistance that must be encountered by swell traveling through regions of calm. The local loss of wave energy per unit time caused by air resistance [SVERDRUP and MUNK, 1946, eq. 84] is

$$R_N = - s(\rho'/\rho)g(E/C) = - s(\rho'/\rho)(2\pi/T)E \quad \ldots\ldots\ldots\ldots\ldots \quad (15)$$

where s = 0.013 and is the "sheltering coefficient," ρ' is the density of the air, and ρ the density of the water. This term has to be added on the right-hand side of (9). Equation (11) then takes the form

$$(1/E)dE/dt = - 1/t - s(\rho'/\rho)(2\pi/T) \quad \ldots\ldots\ldots\ldots\ldots \quad (16)$$

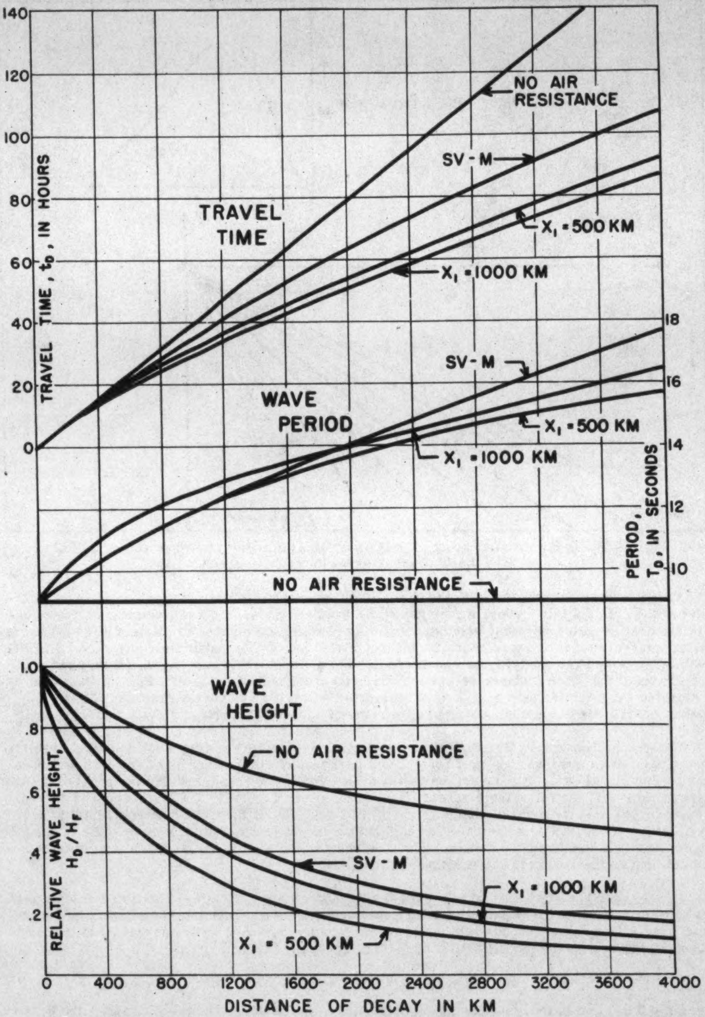

Fig. 4--Travel time, period, and relative height of significant waves as functions of distance of decay, according to the graph by Sverdrup and Munk (Sv - M) for T_F = 9 seconds, and according to Fig. 5 (x_1 = 1000 km) and Fig. 6 (x_1 = 500 km)

Remembering that dE/dt represents the total change in energy along a line of constant period, one obtains by integration

$$\log_e (E/E_1) = \log_e (t_1/t) - s(\rho'/\rho)2\pi (t - t_1)/T_1 \quad \ldots\ldots\ldots\ldots\ (16)$$

or, using (5), taking into consideration that E is proportional to H^2

$$\log_e (H/H_1) = (1/2) \log_e (x_1/x) - s(\rho'/\rho)(4\pi^2/g)(x - x_1)/T_1^2 \quad \ldots\ldots\ldots\ (17a)$$

$$= (1/2) \log_e (x_1/x) - (K/T_1^2)(x - x_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (17b)$$

where $K = 6.37 \times 10^{-7}$ ($\mathrm{cm}^{-1}\mathrm{sec}^2$).

It follows from (17) that over a given distance, $x - x_1$, the decrease in height must be larger than according to (13b), and that the short-period waves decrease faster than the long-period ones. Consequently, the height maximum must shift toward the longer waves. The travel time which is obtained from the group velocity of these longer waves is shorter than the travel time without air resistance. Thus, the modifications are all in the direction indicated by the observations.

It remains to be shown that (17) gives numerical results in approximate agreement with observations. Since the first term on the right-hand side of (17) depends upon the ratio x_1/x, whereas the last term depends upon the difference $x - x_1$, the rate at which H decreases for a given distance $x - x_1$ depends upon the value of x_1. The larger x_1, the slower will be the decrease. We shall examine two cases, $x_1 = 10 \times 10^7$cm (1000 km) and $x_1 = 5 \times 10^7$cm (500 km). In each case we shall assume that at $x = x_1$ the wave height is at a maximum at T = 9 seconds. Taking x_1 as the length of the fetch and identifying the highest waves with the significant waves, we find from the graphs for generation of waves that in the first case a wind of 23 knots must have blown for 54 hours over a 1000-km (540-mile) fetch, that in the second case a wind of 35 knots has blown for 27 hours over a 500-km (270-mile) fetch.

The assumption that the waves at the end of the fetch can be considered as centered impulsively generated waves, represents an over-simplification. Actually, the value of x_1 may differ for the different parts of the wave spectrum and may vary within the same part of the spectrum. Waves for which x_1 is small will, according to (17), decrease rapidly in height and will soon disappear from the spectrum of the swell. In (17) x_1 may therefore be interpreted as applicable to those waves at the end of the fetch that have traveled the longest distance, and it is justified to let x_1 represent the length of the fetch. The distance $x - x_1$ represents the distance of decay.

Figures 5 and 6 show the assumed variation in wave height with wave period at the end of the fetch, also the computed variations at different distances of decay, varying from 100 km to 6,000 km. The disappearance of the short-period waves and the shift of the maximum wave height toward longer periods is apparent in both cases. It is also evident that in records of swell the long-period waves, whose significance was discussed by MUNK [1947a], appear prominently because these waves decrease more slowly in height than the waves of shorter periods.

Figure 4 shows a comparison between computed values and those from Sverdrup and Munk's graph. The relative height of the swell, the period and the travel time are plotted against distance of decay. For the computed values the curves refer to the highest waves, assuming that these can be considered the significant waves. The assumption of no air resistance is obviously in complete disagreement with the contents of the Sverdrup-Munk graph, but by taking air resistance into account both examples give an increase in period similar to that obtained from the graph. The travel times, however, are about 15 per cent shorter and the decrease in wave height is faster, particularly with $x_1 = 500$ km. The overall agreement is better with $x_1 = 1000$ km. One could select such values of x_1 and of $H = H(T)$ for $x = x_1$ that a close agreement with the results from the graphs could be achieved, except for the travel time which would be shorter, but there is no point in doing so because there exists no observational basis for selecting any particular function $H = H(T)$, nor any basis for assigning a particular value to x_1.

The fair numerical agreement obtained indicates that the processes considered here are responsible for some of the characteristic properties of swell. If this is true one should furthermore expect that: (1) Swell from a short fetch decays more rapidly than swell for a long fetch; (2) the period increase of the main swell depends upon the character of the wave spectrum at the end of the fetch which, in turn, may depend upon the length of the fetch and upon the wind velocity; (3) the travel time of the main swell is probably about 15 per cent shorter than according to the Sverdrup-Munk graph.

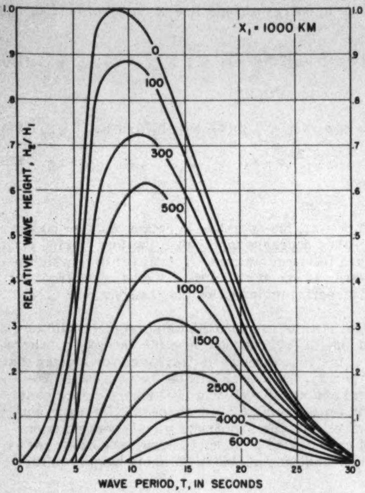

Fig. 5--Assumed variation of wave height with period at the end of a 1000-km fetch (curve marked 0) and computed variations at distances of decay ranging from 100 to 6,000 km

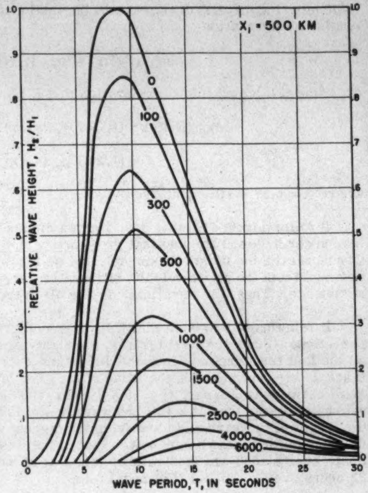

Fig. 6--Assumed variation of wave height with period at the end of a 500-km fetch (curve marked 0) and computed variations at distances of decay ranging from 100 to 6,000 km

A few observations do indicate that the travel time is shorter than obtained from the graph, but many more observations are needed for further examination of this and the other features.

Effect of viscosity--In order to consider the effect of viscosity, it is necessary to add the term [LAMB, 1932, p. 624]

$$-4\nu(2\pi/T)^4 E/g^2$$

to the right-hand side of (9). Here, ν is the kinematic viscosity of water which for sea water of temperature 15° and salinity 35 ‰ has the value 0.012 (cm^2/sec). Introducing this term and retaining the term for air resistance gives

$$\log_e(H/H_1) = (1/2)\log_e(x/x_1) - (\rho'/\rho)(s/g)(2\pi/T)^2\,[1 + (\rho/\rho')(4\nu/sg^2)(2\pi/T)^3]\,(x - x_1)$$

With the above value of ν one obtains for the last term in the parenthesis

T =	5	10	15	20 sec
Term =	6.2×10^{-3}	8.2×10^{-4}	2.3×10^{-4}	9.8×10^{-5}

Thus, the effect of ordinary viscosity is negligible, and swell traveling through regions of calm is not influenced by viscosity. With a weak wind even the accompanying eddy viscosity would have no effect and it may therefore be concluded that viscosity need not be considered when dealing with the decay of swell.

Effect of weak following and opposing winds--The effects of weak following and opposing winds (C > U) can be treated by adding to the right-hand side of (9) the complete term representing energy transfer. For a following wind this term is

$$E(\rho'/\rho)(2\pi/T)\,[2\gamma^2(U/C)^2 - s(C - U)^2/C^2] \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

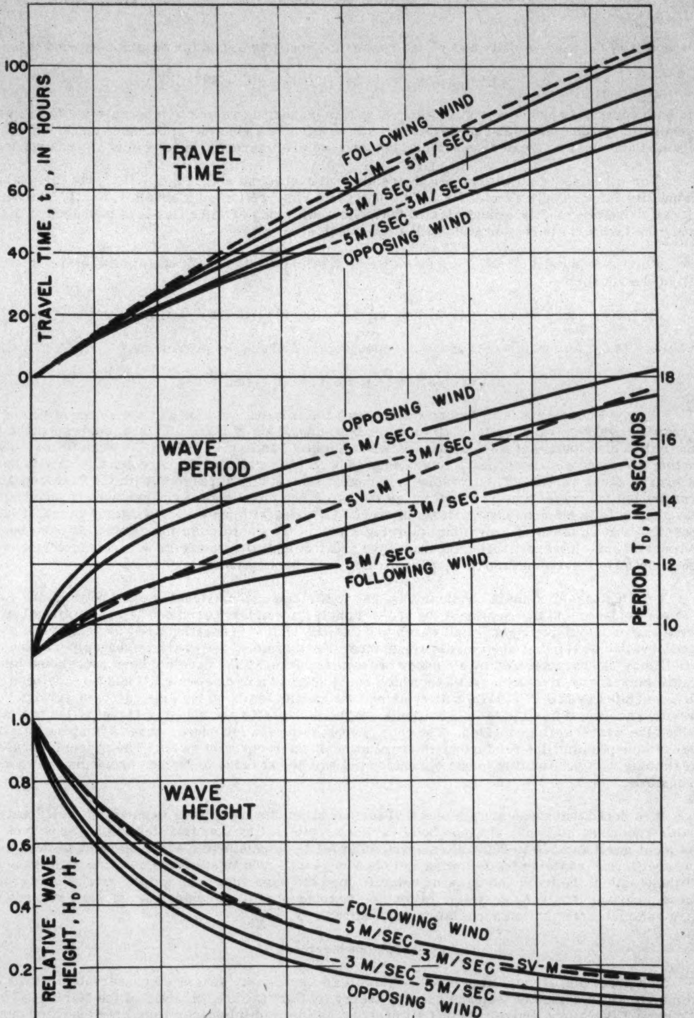

Fig. 7--Travel time, period, and relative height of significant waves as functions of distance of decay according to the graph by Sverdrup and Munk (Sv - M) for T_F = 9 seconds, and according to computations, assuming the initial variation of height with period shown in Fig. 5 for x_1 = 1000 km (curve marked 0) and following or opposing winds of 3 and 5 m/sec

where U is the wind velocity and γ^2 the resistance coefficient, and for an opposing wind it is

$$E(\rho'/\rho)(2\pi/T)[-2\gamma^2(U/C)^2 - s(C+U)^2/C^2] \tag{19}$$

In both cases it is assumed that $C > U$, but this is no serious restriction because for $C < U$ wave generation takes place. For moderate and strong winds the generation becomes an important feature and must be treated separately, but here we are interested in the effect of weak winds.

For winds above about 6 m/sec the resistance coefficient equals 2.6×10^{-3}, but for weaker winds its value is only about 0.9×10^{-3}. The sheltering coefficient s equals 1.3×10^{-2} as before. It can therefore readily be ascertained that with weak winds of velocities less than about 6 m/sec only the last term in (18) or (19) needs to be considered.

For following and opposing winds less than 6 m/sec the decay of swell is therefore obtained from the equation

$$\log_e(H_2/H_1) = (1/2)\log_e(x_1/x_2) - (K/T^2)[(C \mp U)^2/C^2](x_2 - x_1)$$

where - is for following winds and + for opposing, and where, as previously,

$$K = s(\rho'/\rho)(4\pi^2/g) = 6.37 \times 10^{-7}\ (\mathrm{cm}^{-1}\ \mathrm{sec}^2)$$

Figure 7 corresponds to Figure 4 and shows the relative wave height, the apparent period increase, and the travel time for following and opposing winds of 3 and 5 m/sec, corresponding to the initial distribution of wave energy shown in Figure 6 and x_1 = 1000 km. A weak following wind, acting over long distances, leads to a change in height of swell that is more consistent with the Sverdrup-Munk curves. The increase in period is still in fair agreement with the Sverdrup-Munk results but the travel time is shorter than theirs. Since the meager evidence used to substantiate the graphs is based upon observations in middle latitudes with prevailing westerly winds, it is possible that an effect of prevailing following winds is incorporated in the graphs. It must be emphasized again, however, that one cannot give great weight to agreements between numerical results because there exist too many possibilities for adjusting them.

Conclusions--The main conclusion is that no striking inconsistencies exist between the empirical evidence and the results of the present analysis which is based on the assumptions that the wind raises impulsively generated waves and that beyond the generating area these advance as conservative waves that meet an air resistance. Furthermore, the analysis suggests that the swell may be characterized by a number of features which so far have not been recognized because no records have been available which could reveal their existence. It has already been demonstrated by MUNK [1947b] that by using conclusions based on the kinematics of surface waves, records of swell give information as to the distance to and speed of travel of the storm in which the waves were generated. The energy considerations introduced here have opened a number of new possibilities for further interpretation of the records of swell. The present discussion deals only with propagation in one dimension but can be expanded to include problems in two dimensions.

It is hoped that these suggestions will further stimulate the efforts to establish well located swell-recording stations. It would be of particular interest to have two stations in the path of frequent swell and 500 to 2000 miles apart, in order to determine the accurate value of the sheltering coefficient, examine the following and opposing winds, and to study the possible significance of the length of the fetch and the wind velocity upon the wave spectrum and the rate of decay. For these purposes it is very desirable to develop instruments for rapid analysis of wave records which give complete information about the wave spectrum.

Acknowledgments

The preceding attempt at dealing with swell as impulsively generated conservative waves was stimulated by a series of lectures on wave theory by Carl Eckart, Director of the Marine Physical Laboratory, University of California. The ideas in this paper have been clarified during discussions with my collaborators, R. S. Arthur and W. H. Munk.

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Suggestions as to Future Research in Ground-Water Hydrology

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Abstract--Determination of the ground-water supply available from any aquifer or in any specified area requires not merely the application of specific quantitative methods but also a broad and accurate knowledge of the geologic, hydrologic, and geochemical factors that are involved, and consideration of the economic and legal limitations. Further research is needed as to geologic texture and structure in relation to the occurrence and movement of the water; the precise nature of specific yield, which determines the effective storage capacities of the aquifers; the molecular physics involved in the downward and upward movement of water in the zone of aeration, and quantitative evaluation of ground-water recharge and discharge; the hydraulics of ground water, as studied by pumping test methods, with special reference to boundary conditions; studies of perennial yield of aquifers of low permeability; the genesis of the mineral contents of ground water as determined through appropriate geologic, hydrologic, and chemical studies; and methods of geophysical exploration and well logging for determining the occurrence of ground water. Serious study is also needed as to practicable methods of implementing the recently developed principles and methods of ground-water hydrology in the production of water supplies and the economic and legal problems involved.

In both surface- and ground-water studies much emphasis has been placed throughout the years on quantitative methods and results. This has been in response to the practical necessities of those who develop water supplies for information as to the quantity of water available. In surface-water work, stream gaging has been of major importance. In ground water the quantitative approach is more obscure, but various methods have gradually been developed for determining the ground-water recharge and discharge and the "safe yield," by which is generally meant the perennial yield under certain prescribed limitations of practicable development. Gradually it has become evident that quantitative problems can not be solved by rule of thumb but require broad and accurate knowledge of the geologic, hydrologic, and geochemical factors that are involved.

It is inevitable that in ground-water hydrology, as in any other branch of science, principal interest and progress should be once along one line and then along another. Thus at different times interest has been focused on water-stage recorders and the great variety of fluctuations that they record, discharge by transpiration and the functioning of different phreatophytes, salt-water encroachment, the elasticity of artesian aquifers, the molecular forces controlling ground water and soil moisture, permeability, the development of the cone of depression, and other factors. It is wholesome, however, to attempt to take a comprehensive view of the entire subject, the present status of our knowledge, and the phases of the subject in which more vigorous research is needed. The present brief paper is intended to be suggestive only. Perhaps it ought to be the forerunner of a conference at some future meeting on a research program in ground-water hydrology. In addition to covering the subject of ground-water hydrology in a more detailed manner, this conference could help to establish a closer relationship with the allied fields of petroleum and soil mechanics. The fundamental problems in these fields are in many cases similar to those in ground water, and theories, methods, and techniques can often be interchanged to mutual advantage.

Recently the principal interest has been in the hydraulics of ground water, as studied by pumping-test methods. For many years knowledge in this field was more or less static and there was a complacent willingness to accept the results of early workers as the final word. In the last ten or fifteen years, however, there has been a brilliant revival of interest and revolutionary progress in this field. We are now mid-stream, as it were, and much more work must be done to interpret, orient, and apply the newly developed methods. As mathematics are applied more and more to the basic principles of ground-water flow, additional methods will be developed. These new methods should be simplified and standardized in so far as possible for field application on a wide scale. These studies will ultimately be expedited by use of electric models in place of elaborate computations.

At first the results were given merely on the assumption that the aquifer is uniform and indefinite in extent, but now the effort is to interpret the results in terms of boundary conditions;

that is, places of change in transmissibility, or where the aquifer pinches out or is terminated by a fault, or, on the other hand, areas where recharge occurs. In the course of time more comparisons between computations and actual long-term observations will become available, and these should be studied with a view toward refining the methods by which the computations were made and detecting the geologic irregularities and opportunities for recharge that were not shown by the tests.

The principles of ground-water hydraulics have been applied chiefly to the productive aquifers which furnish large water supplies. However, the less productive formations are also of immense importance because over large areas they are almost the only practicable sources of water supply. Relatively little attention has been given to the application of scientific methods to these less productive formations. Data ought to be obtained on the pumpage from established wells and well fields, the size and shape of the cones of depression developed by this pumpage, and the mode and quantity of recharge in wet seasons. With this information it would be possible to arrive at conclusions as to the perennial yield per unit of area under optimum development, the extent of water supplies that remain available for development, and the practicable methods of recovering this water when needed.

There has long been interest in the obscure and apparently peculiar behavior of the water in the zone of aeration caused by the operation of molecular forces, but there is need for more thorough investigation that is applicable to the problems of ground-water recharge, storage, and discharge. Much more definite and reliable information is needed not only as to the processes by which water moves from the surface to the water table and vice versa, but also the quantitative evaluation of these processes. Likewise, the whole subject of specific yield needs quantitative clarification as to the process, amount, and rate of unwatering when the water table declines. With the re-establishment of the hydrologic laboratory in the United States Geological Survey, it is hoped that intensive work can be started in this important subject, but much cooperation is needed, and the problems will have to be studied in the field as well as in the laboratory.

Infiltration from streams is becoming increasingly important as larger and larger quantities of water are withdrawn from aquifers recharged by the streams. Much has been learned about the processes involved, but more remains to be learned concerning such matters as the effects of changing stage in the streams, silting of the beds, seasonal fluctuations in the temperature of the water, and fluctuations in the amount of dissolved and suspended matter in the water. More effective methods are needed for predicting perennial yields of wells near streams. In many instances today where aquifers are said to be overdeveloped this is not strictly true. There still remains the possibility of artificial recharge, and in some places this would be an economical procedure. One of the principal reasons that artificial recharge has not been practiced on a wider scale is the lack of authoritative information concerning the methods that should be used and the results to be expected. More data should be obtained and published concerning the installations now in existence. Much research is still needed to determine the efficiencies of various methods and the capacity of aquifers of different kinds to receive and hold the water.

The United States Geological Survey makes periodic measurements of water levels or artesian pressure in about 7,000 observation wells and maintains automatic recorders on about 350 of these wells. The resulting data are published annually in a series of six Water-Supply Papers. These Papers also contain interpretive text and graphs, but thorough study has been given chiefly to the records of wells in areas of heavy pumping. There is need for a well planned program of intensive study of the water-table wells that are not greatly affected by pumping, to determine the precise causes of the fluctuations, with special reference to recharge, storage, and discharge. An effective beginning has been made in the study of the observation wells in the basin of the Susquehanna River by engineers of the Pennsylvania Water and Power Company, but this is only a beginning. An adequate program of investigation will probably result in the elimination of many of the wells that are now being measured and more effective use of certain key wells.

Methods of geophysical exploration must receive more study. Deep-well current meters and conductivity apparatus have long been successfully used, and recently there has been productive research in the interpretation of electric logs with reference to ground water. This subject and related methods of exploring wells will certainly receive much more investigation and will contribute substantially to the study of ground-water conditions It now appears that, under appropriate conditions, the surface electric resistance method can be applied usefully in conjunction with test drilling, in locating water-bearing deposits and underlying bed-rock surfaces where the deposits and rock surfaces occur at shallow depths; also for detecting bodies of salty water at considerable depths. It appears, however, that the results are too uncertain to warrant elaborate mathematical interpretation, and that the best use of the method may be in simple shallow work and in somewhat deeper salt-water work. The seismic method may be better adapted for determining bed-rock surfaces.

The recent advance in ground-water hydraulics has not been paralleled by equally intensive geologic studies, and there has been a tendency to be satisfied with the stereotyped explanations of the occurrence of ground water. In recent years, however, there has been notable progress along some lines; for example, the effects of faults and dikes upon the occurrence and movement of ground water, and at present studies are in progress on such subjects as the precise mode of occurrence of water in limestone terranes and in terranes of crystalline rocks and the occurrence of solution channels in sandstones. Such fundamental studies should receive more serious attention by the ground-water geologists.

Another vast field that deserves much more study is that of the geochemistry of the ground water. Many good ground-water analyses have been made, the geologic horizons of most of the samples are well determined, and the general chemical character of the waters in the different aquifers is fairly well known. However, more serious attention should be given to the whole subject of the geologic conditions and chemical processes that account for the kinds and quantities of mineral substances that are found in the different waters and the chemical work that these waters are doing. This subject reaches deeply into both geology and chemistry but is the primary responsibility of the students of ground water. Closely related to this subject are those of the thermal springs and the waters which in the past have produced the ore deposits. It is encourging that ground-water geologists are now working with metalliferous geologists on several investigations relating to the chemical work of ancient and modern ground waters.

One of the major problems created by heavy pumping, especially in coastal areas, is that of salt-water encroachment. In some places salt-water encroachment has progressed to a disastrous extent before being discovered, and in other places there has been fear of salt-water encroachment not warranted by the conditions. This confusion is due partly to lack of information regarding the structure and character of the water-bearing materials and the location of salt water in them, and partly to inadequate understanding of the hydrologic laws governing salt-water occurrence and movement. More studies of this subject are needed, especially as to encroachment of salt water on the fresh water in heavily pumped aquifers.

A subject of great practical importance is the contamination of ground water with bacterial pollution and industrial wastes, and the capacity of the water-bearing materials to screen out or eliminate the bacteria and other objectionable substances. This is a border-line subject that has not received adequate systematic study by either the sanitary engineers or the ground-water hydrologists and on which coordinated effort is needed. Various methods for attacking these problems are available. Recently valuable results have been obtained in studies of wells that are supplied by water derived from nearby polluted streams, and these installations provide the means for further study.

The men and women who are engaged in the study of ground-water hydrology have been trained as geologists, engineers, physicists, or chemists, generally with little or no instruction in the specific subject of ground-water hydrology. Some of them, unfortunately, fail to make the effort to become well-rounded hydrologists. It is necessary that there should be specialists within the field of ground-water hydrology, as the subject has become too large and intricate otherwise to be cultivated adequately. However, it is also necessary, for the best results, that these specialists should understand all the fundamental principles, methods, and problems encountered in the field as a whole, so that their specialized efforts may be properly directed. Thus, our personnel must consist of ground-water hydrologists, not simply of geologists, engineers, physicists, and chemists.

Progress is being made in the application of the principles of ground-water hydrology to the practical problems of the recovery, utilization, and conservation of ground-water supplies, but inevitably the application lags behind the scientific development. It is much to be desired that the engineers and other technical men concerned with the production of water supplies should become as expert in ground water as they are in surface water, for this is necessary to obtain thoroughly sound and effective engineering technique in the entire field of water supply.

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FURTHER STUDIES OF THE BALANCED WATER CYCLE ON EXPERIMENTAL WATERSHEDS

J. A. Lieberman and P. W. Fletcher

Abstract--In the field of land-use hydrology it is frequently of value to keep a chronological account or balance of the components of the water resource of a watershed. In this paper a time period for studying this balance is described. Essentially it is the annual period between times of maximum watershed storage at the end of the dormant season. Changes in ground-water storage are taken into account, and by choosing the beginning and end points of the year at times of field capacity, water storage changes in the soil mass are eliminated. Sample data for an experimental watershed are given.

In the management of water resources, it is of considerable value to be able to keep accounts of the resource in all of its phases of the hydrologic cycle. This is particularly true when an attempt is made to evaluate the effects of land use changes and land management practices on several components of the water cycle. Much progress has been made in establishing practical accounting methods with the use of the storage equation inflow = outflow ± storage and other balancing procedures [see "References" at end of paper; HURSH, HOOVER, and FLETCHER, 1942; HOYT and others, 1936; HOUK, 1921; VERMULE, 1894].

At the Coweeta Experimental Forest, an expansion of a study of these methods is continuously being carried on. The experimental forest which is part of the Appalachian Forest Experiment Station is located in the high rainfall area of the southern Appalachian Mountains. The data presented in Table 1 give a general summary of the rainfall and runoff for the period of record for the experimental drainage basin (no. 18) used in the present paper. This watershed is 30.8 acres in area and is at an average elevation of 2700 feet. The basic geology is the Carolina gneiss of Pre-Cambrian age. The soil is more than 4 feet in average depth and lies over soft, disintegrated rock. The vegetal cover is a typical hardwood forest stand of the southern Appalachian Mountains.

Table 1--Average monthly precipitation, runoff, and temperature for the period 1936 to 1945, Coweeta watershed 18

Month	Precipitation	Runoff		Temperature
	in	in	per cent	°F
Nov.	4.32	1.10	25.5	43.9
Dec.	7.24	1.93	26.7	38.8
Jan.	5.79	3.37	58.2	38.1
Feb.	7.50	4.83	64.4	39.9
Mar.	7.64	5.41	70.8	47.3
Apr.	5.89	4.76	80.8	56.4
May	4.21	3.47	82.4	64.1
June	4.56	2.09	45.8	71.1
July	7.34	1.93	26.3	72.0
Aug	5.76	1.66	28.8	71.5
Sep	4.41	1.19	27.0	65.6
Oct.	3.08	0.94	30.5	55.8

In this paper an effort is made to keep a more logical account of the factors of the water cycle by using the same basic expression of the hydrologic cycle given in the above equation but for periods which are believed to be of more hydrologic significance. Previous similar analyses have been made by months for water years of 12 months' duration. In this study a water year, subsequently termed a hydrologic year, is determined by the occurrence of a major storm at the end of the dormant season. The period thus defined will be of only approximately 12 months' duration. In addition to the use of a major storm in the spring to determine the beginning and end of the hydrologic year, levels in ground-water wells were used to check and define more accurately those times. In every case the dates chosen coincided with the most significant rises and peaks in the well levels. At these times the soil moisture is at field capacity, retention storage opportunity is at a minimum and for practical purposes may be considered to be zero; and the ground water stored is at the maximum for that particular hydrologic year. It is felt that because of these factors the hydrologic status of the watershed at such a period of the year is more qualitatively constant from year to year than at any other time. In addition soil moisture is quantitatively constant from year to year at these times. It may further be said that the period is the divide between accretion and depletion of total watershed storage.

Other workers [HOYT and others, 1936; HOUK, 1921; VERMULE, 1894] have described water years divided into various monthly durations based on periods of vegetation growth, soil moisture accretion, and ground-water storage, but in all cases the year has been of arbitrary 12 months' duration. PARKER [1932, p. 183] stated "if the period at which the water stored up in the ground is at a maximum could be definitely observed, the relations of the rainfall to runoff for the intervals between these maxima would be more constant than for any other period." HOYT and others [1936] in their study of the Skunk River Basin in Iowa used September as the beginning of the accretion, and the tabulated data and computations indicate that April is generally the dividing month between accretion and depletion. PARKER [1932] also stated that "the difficulty lies in the fact that these maxima are, so far as present information exists, somewhat more irregular in time than the minima in stream flows and are less easily observed." He also agrees "that the date of maximum storage of ground water has theoretical advantages" and, thus, it appears evident that the difficulty he mentions is one that stems from a lack of hydrologic data and which, in the present study, is overcome by the availability of such data. Adequate well records have made possible the observation of the "period at which the water stored up in the ground is at a maximum."

In the humid, high-rainfall area of the southern Appalachians, it also appears that there is actually more regularity in the periodicity of maximum total watershed storage than there is in the time of minimum stream flows. This may be attributed to the seasonal distribution of rainfall, the influence of vegetation, temperature, and in case of this particular watershed, to the nature of the soil profile. Since the vegetation demand remains essentially the same from year to year and the monthly distribution of rainfall is fairly uniform and there is no change in the soil surface or profile, it follows that the opportunity for watershed storage is constant from year to year and that maximum watershed storage will be reached with comparative regularity each hydrologic year.

Rainfall and runoff of the drainage basin under study have also been discussed in other papers [HOOVER, 1944]. The relationship between rainfall and runoff corrected for increments to, or decrements from, ground-water storage for the hydrologic yearly periods is of interest. The correction for ground-water storage is simply an integration of the area under the composite depletion curve of ground-water flow or can be made more directly by use of a storage curve after SNYDER [1939]. The result of the regression analysis made is shown in Figure 1. The x-intercept of the linear equation is noted to be 38.69. In statement form, it is construed that 38.69 inches of precipitation represents what is commonly known to hydrologists as rainfall losses to runoff for a mean hydrologic year.

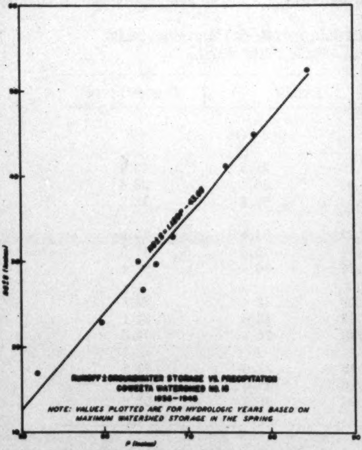

Fig. 1--Relation of runoff corrected for storage to precipitation for nine hydrologic years

Table 2 is a balance sheet of the water cycle components on watershed 18 for the nine hydrologic years of record. P is precipitation, RO is runoff, Q is average rate of runoff during the last day of the hydrologic year, S is storage, and E is evaporation. The dates are the beginning and end of the hydrologic year. The closing dates are 48 hours after the cessation of the major storm and are further specified by ground-water well level observations as previously indicated. Columns 1 and 2 are the total amounts of precipitation and runoff respectively for the periods noted. Column 3 is the mean daily discharge in cubic feet per second per square mile for the year-end day, and Column 4 is the change in ground-water storage from one hydrologic year to the next. Decreases are noted by minus signs. The actual amount of ground water in storage is not known, and 0.5 csm is used as the zero base for the storage curve.

In expanding the primary equation inflow = outflow ± storage so as to have more intimate knowledge of the various factors making up the water cycle, the form of equation $P = RO \pm S + E + T \pm R$ is commonly used. In keeping running accounts or accounts over a definite period of time P, RO, E, and T (transpiration) are kept as summations or totals for the period, and S and R are changes in ground-water storage and retention storage, respectively, from the beginning to the end of the period. By choosing the hydrologic year as described, the R factor is eliminated since the soil moisture is at field capacity at the beginning and end of the year. Assuming a yearly T of 17 inches, as has been estimated by HOOVER [1944] based on actual removal of forest vegetation on an adjacent experimental watershed, E (Column 6) may then be determined being the only unknown remaining in the expanded equation.

Table 2--Balance sheet of nine hydrologic years, Coweeta watershed 18

Year (dates inclusive)	P (1)	RO (2)	Q (3)	S (4)	RO+S (5)	E (6)
	in	in	csm	in	in	in
Apr. 1, 1936-Mar. 9, 1937	78.02	44.33	3.99	0.60	44.93	16.09
Mar. 10, 1937-Mar. 24, 1938	64.65	26.58	4.08	0.16	26.74	20.91
Mar. 25, 1938-Mar. 14, 1939	84.52	47.41	8.21	5.03	52.44	15.08
Mar. 15, 1939-Apr. 25, 1940	59.71	27.60	4.31	-4.66	22.94	19.77
Apr. 26, 1940-Mar. 25, 1941	51.91	20.96	2.07	-3.97	16.99	17.92
Mar. 26, 1941-Mar. 29, 1942	64.12	24.32	5.45	5.70	30.02	17.10
Mar. 30, 1942-Mar. 25, 1943	74.78	39.61	6.72	1.64	41.25	16.53
Mar. 26, 1943-Mar. 10, 1944	68.39	33.61	6.11	-0.74	32.87	18.52
Mar. 11, 1944-Mar. 1, 1945	66.36	33.25	3.77	-3.52	29.73	19.63
Averages	68.05	33.07			33.10	17.95

Based on field observations, it is known that there are periods during the year other than those discussed here at which soil moisture reaches field capacity. This is particularly the case when high rainfall originating from tropical hurricanes occurs during the summer months. Balances for these periods may be carried in the same manner using that portion of T which occurs in the period.

At present on the Coweeta Experimental Forest the continuous measurement of soil moisture for the entire soil profile is being taken at weekly intervals. This may be extended to include more frequent measurements immediately following storm periods. The lack of such measurements in the past has constituted a serious deficiency in hydrologic data required in the field of land-use hydrology. Since soil moisture is the basic source of E and T, with the addition of these now missing data it will be possible to keep more accurate balances for the water cycle components for any period, and the accuracy of stream flow forecasts will be considerably improved. With this outlook in view, it is evident that this paper is intended as a step towards tightening up present water balance techniques, and at the same time is in the nature of a status and progress report of such techniques.

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APPARENT CHANGES IN WATER STORAGE DURING FLOODS AT PEORIA, ILLINOIS

Max Suter

Abstract--The effect which three floods of the Illinois River at Peoria had on water levels and apparent storage of ground water in a glacial drift aquifer was studied. Continuous water-level records from many wells were utilized to map the ground-water surfaces before, during, and after the floods. These maps, together with a map of the top of the impervious bedrock, allow fairly accurate calculation of the quantity of ground water in storage and of the changes therein. It is shown that the apparent increase in storage is lost immediately with the passage of the flood, although the ground-water levels are always below river stage. Several possible explanations are discussed. The one favored is that which ascribes the rise of the water levels to a pressure effect due to the load of the flood waters, causing only an apparent (not an actual) increase in the amount of water in storage.

In connection with an investigation of the ground-water conditions at Peoria, Illinois, the State Water Survey has made some observations on the variation in the quantity of water stored in the aquifer. The investigation was reported on pages 493-500 of the Transactions of the American Geophysical Union for 1943. This paper is limited to a discussion of the apparent changes in the quantity of water contained in the aquifer as a result of floods on the Illinois River.

Since 1939, the Illinois River at Peoria has been at pool stage (elevation 440.0 feet ± 0.5 ft. mean sea level) above the White House navigation lock and dam except during floods. Several floods have occurred during the last few years. The peak stages at Peoria attained during these floods were: 1943, 457.2 ft.; 1944, 452.2 ft.; and 1945, 448.4 ft.

The character of the three floods studied can be seen from the hydrographs in Figure 1. The 1944 flood was of less height but of longer duration than the extremely high flood of 1943. The flood of 1945 can clearly be classified as a minor flood. Pekin is situated about ten miles below

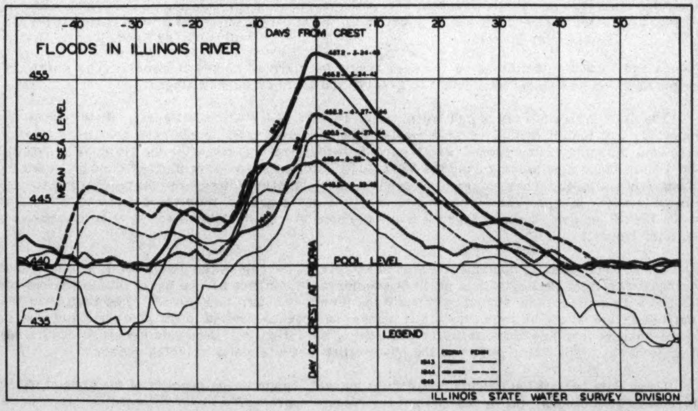

Fig. 1--Hydrographs of floods at Peoria and Pekin in 1943, 1944, and 1945

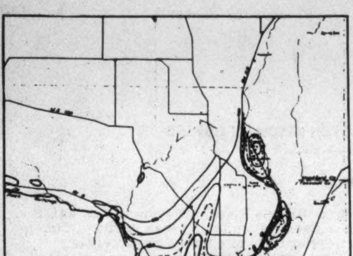

Fig. 2--Contours of ground-water level at Peoria, May 1, 1943

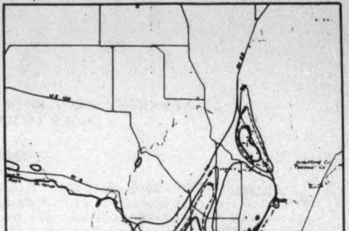

Fig. 3--Contours of ground-water level at Peoria during flood, June 1, 1943

Peoria and about four miles below the dam regulating the pool stages at Peoria. The water stages at Pekin are therefore subject to greater and more frequent changes.

The State Water Survey has 90 wells under regular observation in Peoria. Water-level recorders are installed in 21 of these wells. The observed water levels have been used to prepare detailed maps of the ground-water surface before, during, and after the flood. Figures 2, 3, and 4 show these conditions during the 1943 flood. Similar maps of conditions during the later floods are available. These maps have been used to construct differential maps showing the change in water levels. The increase and decrease in the ground-water levels due to the effect of the 1943 flood are shown in Figures 5 and 6, respectively. Similar maps have been drawn for the later floods.

The ground water is contained in a sand and gravel deposit in the glacial drift which is underlain by water-tight Pennsylvanian shale of considerable thickness. The top of this shale has been mapped with considerable accuracy beneath the territory shown in Figure 7. The aquifer is unconfined except where an impervious silt blanket has been deposited in the river bed and where a clay deposit covers approximately five per cent of the formation. Artesian pressure occurs only in these areas. The water in five of the observation wells is under artesian pressure.

These data permit the calculation of the apparent change in the quantity of the ground water stored by two methods: (a) In one method the volume represented by the differential maps is calculated; (b) for selected conditions within each field the ground-water storage was also calculated by subtracting the volume bounded by the observed water surface and a selected level datum plane

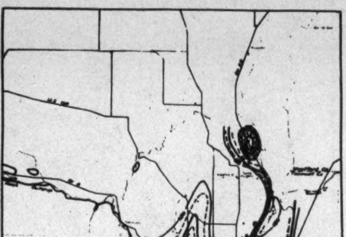

Fig. 4--Contours of ground-water level at Peoria, September 1, 1943

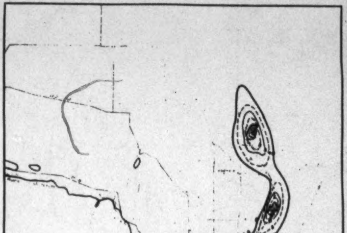
Peoria Differential Contours.
Rising Water May 1-June 1 1943.
showing change of water levels in feet
N
Scale

Fig. 5--Differential contours showing the rise of water by flood of 1943

above the water surface from the volume bounded by the same level datum plane and the bedrock surface. The difference between the storages at the various stages gives the changes in storage. The results obtained from the two methods are fairly consistent.

In this paper the term "field" has been used to designate an area within which wells affect each other. The investigation showed the existence of several distinct fields in the Peoria Area. Pumpage in any field had no effect upon wells located in adjacent fields. Calculations are made for each field and totalled for the several fields.

Table 1 shows calculations of the quantity of water stored in the several fields that were obtained by Method (b).

Direct measurements of voids in many sand samples obtained from drilled wells indicate that the voids in the material vary from 27 to 35 per cent. In these calculations an average of 30 per cent voids has been used.

The pumpage from each field in millions of gallons per day was as follows: Sankoty, 10.2; North, 5.7; Central, 48.2; and Pekin, 20.2; with a total of 84.3.

The maps of the ground-water surface indicate that the ground-water level in all four fields is at all times below the river stage. The ground-water level rises with a rise in the river stage and starts to recede immediately after the flood crest has passed. Figures 8 and 9 show some typical diagrams obtained in 1943 in the Central Field and in the North Field. Similar curves

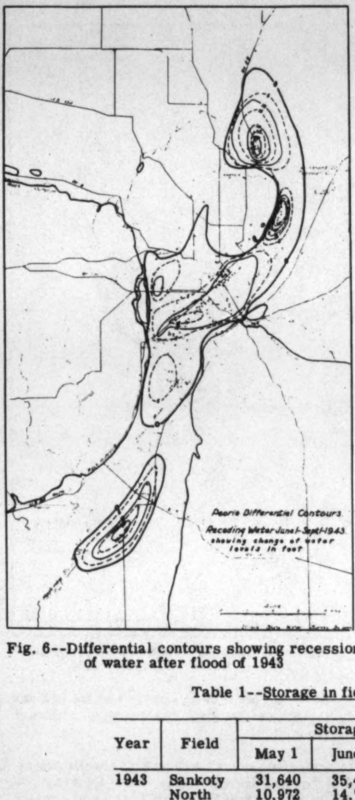
Peoria Differential Contours
Receding Water June 1-Sept 1-1943
showing change of water
levels in feet

Fig. 6--Differential contours showing recession of water after flood of 1943

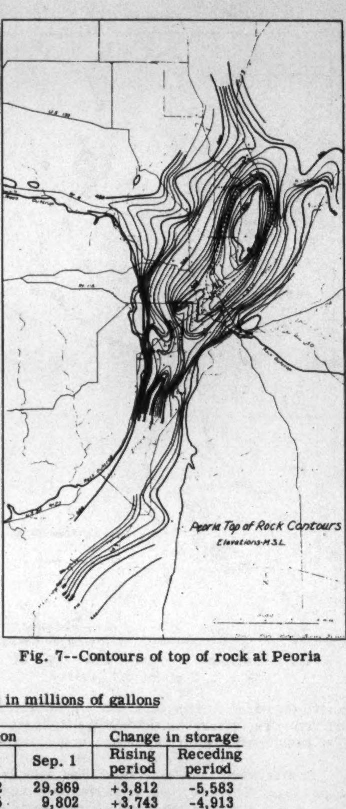
Peoria Top of Rock Contours
Elevations-M.S.L.

Fig. 7--Contours of top of rock at Peoria

Table 1--Storage in field in millions of gallons

Year	Field	Storage on			Change in storage	
		May 1	June 1	Sep. 1	Rising period	Receding period
1943	Sankoty	31,640	35,452	29,869	+3,812	-5,583
	North	10,972	14,715	9,802	+3,743	-4,913
	Central	98,169	112,784	99,784	+14,615	-13,000
	Pekin	19,147	23,666	18,364	+4,519	-5,302
	Totals	159,928	186,617	157,819	+26,689	-28,798
		Mar. 15	May 1	Aug. 1		
1944	Sankoty	30,132	33,355	29,086	+3,223	-4,269
	North	9,464	13,470	9,864	+4,006	-3,606
	Central	97,080	106,306	95,760	+9,226	-10,546
	Pekin	15,172	21,162	16,937	+5,990	-4,225
	Totals	151,848	174,293	151,647	+22,445	-22,646
		May 1	June 1	Sep. 1		
1945	Sankoty	27,615	30,244	28,749	+2,629	-1,495
	North	9,827	11,911	10,447	+2,084	-1,464
	Central	97,124	99,515	95,177	+2,391	-4,338
	Pekin	17,188	20,205	17,263	+3,017	-2,942
	Totals	151,754	161,875	151,636	+10,121	-10,239

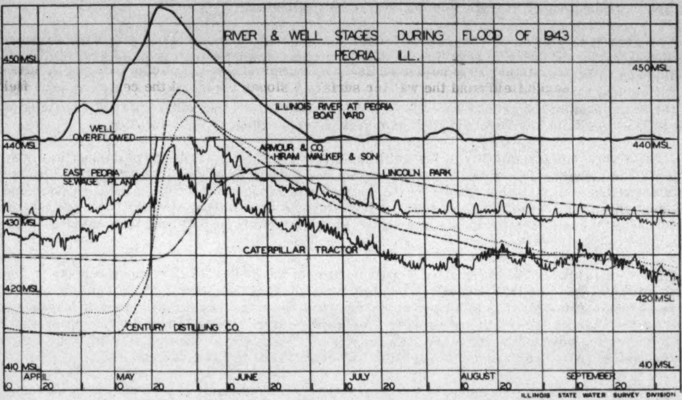

Fig. 8--Hydrographs of river and well stages during flood of 1943

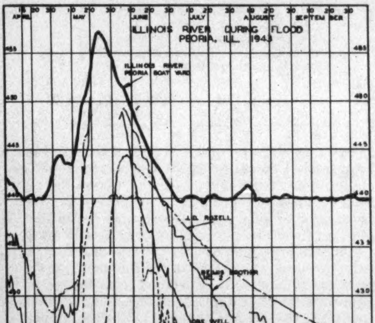

Fig. 9--Hydrographs of river and well stages during flood of 1943

have been prepared for the other fields and for later floods. These curves all have the same characteristics and indicate similar phenomena.

It was first attempted to explain this behavior by the theory that the rise was due to infiltration and the lowering to pumpage. It has been known for several years that when the river stage is at pool level the river bottom is practically water-tight due to extensive silting; thus any infiltration must be due to the flooding of bottom lands or to excessive rainfall in the area. The latter may have an influence, as floods seldom occur on the Illinois River at Peoria without excessive local rainfall. Little is known of the time required for rainfall to reach the ground water in the well field. Temperature and chemical analyses indicate that the changes in the quality of ground water which might be attributed to infiltration of rainfall occur months after the flood has passed. If the rise in ground-water level were due to infiltration from flooded areas, the rise would continue so long as these areas are flooded or until the bowl-shaped basin forming the depression in the ground-water surface was filled. Neither of these two conditions occurs. Actually the ground-water level starts to recede as soon as the flood crest has passed. It is clearly shown by the data that the apparent decrease in the quantity of water stored is greater than the quantity of water removed by pumpage. Calculations show that in 1943 the recession was 3.6 times the pumpage; in 1944, 3.0 times; and in 1945, 1.4 times. Thus the apparent increase in ground-water storage was not caused by infiltration.

Another theory advanced to account for the lowering of the water level is that the water drains out downstream. In order to have a flow of ground water downstream a definite hydraulic gradient would have to be established. Observations indicate that a definite cone of depression exists in each field and the water surface slopes toward the center of the field from all directions. Thus it would be impossible for ground water to flow downstream from the central part of any field. Water levels in all wells in any field show the same trends regardless of their location.

The elastic compressibility of the drift could produce the effect observed during this investigation. The compression is due to the increased load caused by a higher river stage. The readjustment of the soil particles caused by the applied load reduces the voids in the formation and causes a rise in the observed ground-water level without the addition of water from any source. A similar effect has been found in many aquifers; it has also been observed in connection with trains passing near wells.

The Central Field is in a relatively wide portion of the bedrock valley and the river is confined between levees so that the load is applied over only a small portion of the aquifer. The observed ground-water level in this field rises approximately one foot for each foot of increase in river stage. In both the North and Sankoty Fields the bedrock valley is relatively narrow and is to a great extent covered by the river forming a lake. Water-level observations in these fields show a rise of from two to four feet for each foot of increase in the river stage.

The calculated apparent increase in the quantity of ground water stored due to an increase in river stage of one foot is tabulated in Table 2 for three floods studied.

Table 2--Apparent increase in quantity of ground-water storage

Flood	Maximum river rise above pool level		Apparent change in storage per foot rise of river level				
	At Peoria	At Pekin	Sankoty	North	Central	Pekin	Total
	ft.	ft.	millions of gallons				
1943	17.2	22.2	222	218	849	203	1492
1944	12.2	16.2	264	328	755	370	1717
1945	8.4	12.4	313	248	284	243	1088

The changes cannot be explained easily, although they show that the Sankoty, North, and Pekin Fields are similarly affected by all floods, whereas in the Central Field the magnitude of the specific rise varies with an increase of the flood height. This also would be expected from the relative size of the fields and the proportion of the field covered by the flood. In all but the Central Field the ground-water level in the whole area is affected by even small floods whereas in the wide Central Field there is only a small effect of a low flood in wells located over a mile away from the river. Nevertheless, many other factors may distort the picture, such as duration of flood, amount of local rainfall and of capillary water present, variations in the thickness of the drift, in pumpage, and in accuracy of the mapping of the ground-water surfaces from the well data, etc. Therefore, it is not claimed that the pressure effect of applied earth loading is the sole cause of the observed rise of the ground-water level, but that the rise caused by loading is of major importance.

Small-scale experimental tests indicated a rise of one inch for each foot of water load applied to 80 per cent of the area of a sand bed one foot thick. If it is assumed that the water load is applied to only ten per cent of the area and that the drift is 50 feet deep, the calculated rise in ground-water level would be $(1/0.8)(50 \times 0.10) = 6.2$ inches per foot rise of river stage. This is much less than the actually observed value, and further tests are necessary to explain what happens.

Since an apparent rise in water levels can be caused by an applied surface load, increasing the calculated water storage as much as 40 per cent without increase in the actual amount of water present, extreme care must be taken in calculating the amount of ground water stored in an unconfined aquifer by means of observations of ground-water levels. These conditions can be recognized only by long-time closely spaced observations. Because of the idiosyncrasies of each particular aquifer, all factors which might influence the quantity of ground water stored must be evaluated in order that the observations can be intelligently interpreted.

The field work on which this part of the investigation was based was done by A. R. Knodel and the quantity calculations by Virginia Wisegarver, both members of the staff of the State Water Survey Division.

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DISCUSSION

Charles L. McGuinness (United States Geological Survey, Washington, D. C., August 19, 1946)--Suter's paper consists mainly of an explanation of the relation between ground-water and river levels during periods of flood in the Illinois River at Peoria. It has been observed that the ground-water levels, which in several well fields have been drawn below river level by pumping from wells, rise when the river rises and decline when the river declines, but always remain below river level in the well fields. Using a figure of 30 per cent for the specific yield of the water-bearing material, Suter calculates that the amount of water represented by the decline in water level that occurs after a flood is too great to be accounted for by pumping from wells, and that it cannot be accounted for by discharge back into the river because the ground-water levels remain below river level. He also believes that the river bed is essentially impermeable and that the amounts of water represented by the rise in ground-water levels during a flood, assuming a 30 per cent specific yield, cannot be accounted for by influent seepage from the river. He therefore concludes that the rise in ground-water levels is caused mostly by compression of the water-bearing material by the weight of the flood waters, and the decline after the flood is due to elastic expansion of the material.

From the data given by Suter and from general knowledge of the conditions in the Peoria-Pekin area and other areas of generally similar hydrology, it seems to be reasonable to assume that a large part of the rise in water level is due to infiltration of water from the river and a large part of the decline is due to discharge of water back into the river and through wells, so that compression and expansion of the water-bearing material need be assumed to account for only a part of the fluctuation. A small part of the decline is probably caused by discharge of ground water by evaporation in areas between the well fields where the water table is near the surface after floods, but this may not represent an important part of the total.

Suter's paper indicates that the average porosity of the water-bearing material, as determined from samples from wells, is about 30 per cent, and he uses this figure in making the computations of changes in storage shown by the water-table maps. If the porosity averages 30 per cent, the specific yield or "effective porosity" must be less, at least by the amount of retained capillary water. Also, because of stratification and because of the presence of relatively impermeable bodies of clay and silt, the overall specific yield is reduced even further and might be as low as 15 per cent, or even lower. A specific yield of 15 per cent would cut in half the quantities of water involved in the changes in storage, and make it much easier to account for the origin and disposal of the water. Thus in 1943 the amount of water represented by the decline following the flood would have been only 1.8 times the pumpage instead of 3.6 times, and in 1944 it would have been only 1.5 times the pumpage. In 1945 the decline would have represented only 0.7 of the pumpage. If the specific yield is actually as low as 15 per cent and the pumpage was as high as 84.3 million gallons a day in 1945, this would mean that 0.3 of the water reached the wells from some other source, from rainfall or by withdrawal from storage below the levels reached before the flood, or both. If the specific yield was 21 per cent, the pumpage of 84.3 million gallons a day would about balance the observed decline. This would mean that a larger quantity of water would have to be accounted for by means other than pumpage from wells in 1943 and 1944. On the other hand, the pumpage in 1945 might have been less than 84.3 million gallons a day. It would be desirable to have more data on the pumpage at various times during each of the three years, rather than an average for the whole period.

In order to obtain reliable estimates of the specific yield, it doubtless would be a good plan to conduct pumping tests on wells in different parts of the area, rather than to rely entirely on laboratory determinations on disturbed samples. Relatively short-term tests could be made, in order to minimize the effect of uncontrolled changes in pumpage from nearby wells. The whole question as to the amounts of water represented by the water-level fluctuations hinges on the coefficient of storage, and the pumping-test method of evaluating this factor takes into account the stratification and other disturbing factors that may be impossible to evaluate by means of laboratory tests on homogeneous samples. Pumping tests on wells near the river should give results that would indicate directly whether recharge from the river occurs, and tests made on the same wells during both high and low stages of the river should show whether appreciable compaction occurs during floods.

Suter points out that water cannot flow back into the river from the centers of pumpage as the floods pass, because the water levels remain below river level. However, the water-table maps and hydrographs indicate that following a flood substantial quantities of water are able to discharge into the river in the stretches between the well fields, especially between the Central and Pekin Fields, below the dam, and this discharge disposes of some of the water that leaves the river during the rising stage of a flood. This discharge must be considered as a factor in the problem of disposal of the water represented by the fluctuations in ground-water levels; that is, the stretch of the valley including the northernmost and southernmost well fields must be considered as a unit in accounting for the water that enters it and leaves it. Discharge of water back into the river in the stretches between the well fields contributes to the decline of water levels in the well fields because it lowers the water table and reduces the amount of water flowing toward the well fields from these stretches.

Apparently sufficient observation wells are not available at the edges of the river opposite the well fields to show conclusively whether the water table remains below river level at all times. It is possible that the water table might be above river level opposite the well fields for a short time following a flood, so that some water could be discharged back into the river. However, this discharge would be much less than that in the stretches between the well fields.

It is interesting to consider the origin of the water pumped from the wells. If little water infiltrates from the river, it is difficult to account for the origin of the 84.3 million gallons a day that is being pumped. I believe that Suter is of the opinion that not much water flows underground along the valley, and that underflow along the valley can neither account for much of the water that enters the area nor account for the disposal of much of the water. With this I agree. Even on the basis of the most generous assumptions as to width, thickness, and permeability of the water-bearing material in the valley, the gradient is so low that the underflow could scarcely be more than a few hundred thousand gallons a day.

It seems reasonable to assume that the bulk of the water pumped from wells is derived from the main valley, and relatively little from the upland areas, in which the drift consists mostly of till and morainal deposits of relatively low average permeability. The total area of the valley floor and terraces underlain by highly permeable deposits, from a point about a mile north of Sankoty to a point a mile or so south of the industrial wells at Pekin, is on the order of 55 or 60 square miles. Even if we make the assumption that the wells are able to recover all of the ground-water recharge over all of the 60 square-mile area, a ground-water recharge of nearly 2-1/2 feet per year, or about three-quarters of the annual precipitation, would be necessary to supply 84.3 million gallons a day from 60 square miles. It is probable that the average ground-water recharge from precipitation in the Peoria area is much less than this. Therefore, it is necessary to call on other sources of ground water, including withdrawal of water from storage, underflow from the glacial drift adjacent to the main valley, and infiltration from the river. Over a long period of time, withdrawal of water from storage could supply only a small part of the water pumped. An assumption that underflow from the glacial drift adjacent to the valley furnishes as much as a quarter of the water pumped probably would be over-generous, in view of the character of the drift. Therefore, this line of evidence likewise suggests that infiltration from the river forms the source of a substantial part of the water pumped from wells.

Attention is called to Figure 5, showing the net rise of the water table from May 1 to June 1, 1943. It is significant that the greatest rise in water level appears to center in the well fields, not along the river. If the rise is due to compaction caused by the increased load during floods, the greatest rise should occur along the river. The fact that the rise is apparently greater in the well fields than at the river can be explained on the assumption that the rise is due to infiltration from the river. The aquifer is not very thick and is understood to be largely unconfined. Therefore, in the vicinity of the pumped wells the lowering of the water table caused by pumping results in a marked reduction of the saturated thickness, or depth of flow. A rise in the water table some distance away from the pumped wells, caused by a flood, would be accompanied by a greater rise in the vicinity of the wells because of the reduction in gradient associated with the increased depth of flow. Assuming that the ground-water withdrawal is along a line (trench) parallel to the river,

$$h^2_{\text{river}} - h^2_{\text{trench}} = \frac{2\ell Q}{P\,w} \quad \text{(1)}$$

in which h_{river} is the depth of flow at the river, h_{trench} is the depth of flow at the trench, ℓ is the distance between the river and trench, and w is the width of the section, all in feet; Q is the discharge, and P is the coefficient of permeability.

Assuming, as Suter does, that the discharge remains constant, the quantities on the right-hand side form a constant k, and equation (1) may be written

$$h^2_{river} - h^2_{trench} = k \quad (2)$$

Similarly the terms containing the new depths of flow h'_{river} and h'_{trench} resulting from a rise in water level due to a flood must conform to the equation

$$h'^2_{river} - h'^2_{trench} = k \quad (3)$$

assuming the discharge to remain constant. Therefore

$$h^2_{river} - h^2_{trench} = h'^2_{river} - h'^2_{trench} \quad (4)$$

It is obvious that, in order to satisfy the relation in (4), the difference between h_{trench} and and h'_{trench} is greater than the difference between h_{river} and h'_{river}.

At Peoria, owing to the convergence of the lines of flow toward the well fields, the difference between the rise at the wells and that at the river is still greater than if the water were withdrawn from a trench.

Figure 6 shows that the decline in water levels from June 1 to September 1 was greater at the wells than at the river. This, of course, is the natural effect of pumping.

A part of the rise in ground-water levels caused by a flood might represent an artesian effect, but this calls for an assumption that confined conditions exist in the area where such a rise occurs. It is not unreasonable to assume that sufficient beds of silt and clay are present in the water-bearing formation to produce confined conditions in parts of the area beyond the river bottom and beyond the five per cent portion of the area mentioned by Suter. I understand that the logs of many wells in the Illinois Valley in the Peoria area show the presence of some silt or clay. Also, artesian conditions can exist even in sands and gravels that contain no silt or clay, owing to differences in permeability between adjacent beds and especially to differences between horizontal and vertical permeability. However, even if a part of the observed fluctuations are artesian, they must be due mainly to other factors, in view of the fact that the greatest rises occur in the well fields and not at the river.

It might be pointed out that an artesian rise due to loading by the river could not be more than one foot for each foot of rise in the river. The rises of 2 to 4 feet per foot in the North and Sankoty Fields therefore must be due to actual movement of water into the cones of depression.

Even if the river bottom is nearly impervious when the river is at pool stage, a large amount of infiltration may be expected to occur during floods, when the fine-grained material on the bottom is removed or reduced in amount, water is in contact with the upper parts of the sides of the channel, which are inaccessible to the river at low stages and are not subject to silt deposition, and large heads exist for causing water to move outward from the river. Even if the permeability of the river bottom is low when the river is at low stages, the total area of river bottom is large and there may be considerable infiltration into the water-bearing sand and gravel in stretches where the water table is below river level, especially where the pumped wells are only a short distance from the river.

Another feature of Suter's paper that may be mentioned is the experiment of loading a sand bed artificially. Whatever the details of the experiment, extrapolation of the experimental results as given in the paper would appear to be risky. In unconfined, loose-textured granular materials the effect of loading would not extend far from the edge of the load. The distance would depend on the interlocking of the mineral grains. In the laboratory experiment the ratio of the distance between the edge of the load and the walls of the container to the diameter of the mineral grains was relatively small, which would lead to results that could not be extended to the field, where the distance to confining walls is relatively great. Thus it should not be assumed that reducing the area of loading from 80 to 10 per cent of the total surface area of the sand would reduce the average rise caused by loading to exactly one-eighth of an inch per foot of water load.

Neither should it be assumed that increasing the thickness of the sand would result in a proportional increase in the rise of water level. On this assumption, if the experimental sand bed had been 50 feet thick, the rise caused by a foot of load would have been 50 inches. This would be impossible unless the sand were initially in an extremely loose state, as it may have been in the experiment. If the sand in nature were once sufficiently loose to permit such a rise, the effect of repeated loading by floods would long since have made it much more compact. Even assuming that a 50-foot bed of sand could be so loosely packed that a foot of water load could compact it enough to cause a rise in water level of 50 inches, it is incredible that removal of the load would cause the sand to expand to the former loose state.

It is understood that the Illinois State Water Survey is preparing a report on the Peoria area, containing the data that have been obtained during the investigation. This will be helpful to all interested hydrologists, as it will permit a thorough comparison of the different possible interpretations of the water-level fluctuations in the area.

R. G. Kazmann (Ranney Method Water Supplies, Columbus, Ohio, August 19, 1946)--McGuinness' discussion, as well as Suter's paper, are before me as I write these comments. McGuinness' discussion covers the situation admirably and I agree with him in almost every detail. The rise in water levels in the Peoria area can be satisfactorily explained only on the basis of the infiltration of river water. McGuinness makes the following points with which the writer agrees:

(1) Suter's figure for specific yield is too high.
(2) The pumping average used is probably misleading as there is a considerable variation in ground-water withdrawals throughout the year.
(3) The differential rise in water levels, the rise being greatest in pumped areas away from the river, contradicts the "adjustment to load" theory.
(4) Artesian effect is never greater than one-to-one in respect to loading.
(5) Infiltration can be expected to occur during floods in spite of lack of infiltration during low water. This is because bed scouring will occur during high river stages, removing the silt blanket and permitting water to enter the aquifer.
(6) The experiment mentioned by Suter cannot reasonably be extrapolated for large areas and great thicknesses of strata. Besides, repeated loading, caused by floods, would have compacted the formation long before the first well was drilled.

In addition, reference is made to the hydrographs of Figure 8. The well at the Century Distilling Company responded readily to the river rise, but three months after the river went down, its water level was still about eight feet above the level recorded in April. An almost identical remark applies to the Lincoln Park well and the Armour and Company well. These wells are apparently at some distance from the center of pumpage and are not effected by minor pumpage fluctuations. A difference of eight feet, using Suter's 30 per cent specific yield, means a net gain in storage of nearly 800,000 gallons per acre. Using a smaller specific yield will decrease the computed gain in storage proportionately. This gain in storage is directly associated with the river rise, as the hydrographs show. River infiltration is the most likely answer.

The paper states that temperature and chemical changes "in the quality of ground water which might be attributed to infiltration of rainfall occur months after the flood has passed." Assuming that all water pumped by the well is infiltration from rainfall, why should more water infiltrating from rainfall exhibit different temperatures and chemical characteristics? The source of mineral characteristics would be the same in both instances and the water temperature of the entering rainfall would be modified to assume the same characteristics as the water which entered at the same period during previous years.

With regard to temperature characteristics of wells drawing water from an aquifer supplied by river infiltration, Figure 10 summarizes the experience at the Indiana Ordnance Works. There, river infiltration is known to exist. Although the wells, averaging a total pumpage of 40 mgd, are located at the edge of the river, nevertheless, from six to twelve weeks are needed before a change in trend of the river temperature is reflected in the temperature of the well water. If the wells were at a greater distance from the river, many months might elapse before the analogous temperature changes would be noticed.

Suter remarks that pumpage in any of the several distinct well fields in the Peoria area had no effect upon wells located in adjacent fields. The conclusion may be drawn that either the well fields are in separate aquifers or that a source of water is supplying the well fields and this source is so near that it masks the interference effects. It does not seem likely that the well fields are in separate aquifers.

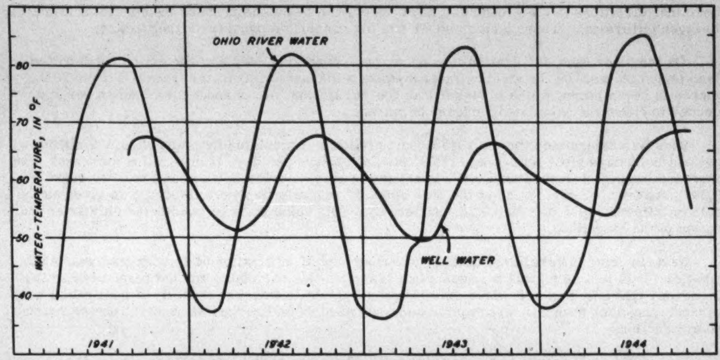

Fig. 10--Thermographs of Ohio River water and water pumped from wells of Indiana Ordnance Works, Charleston, Indiana

In this connection it might be noted that a single Pleistocene aquifer, which is largely under water-table conditions, in the Grand Prairie region in Arkansas and which extends throughout an area of 1,000 square miles, reflects changes of pumpage from one end to the other. Even small changes in pumpage due to the replacement of wells by a surface-water reservoir near, for instance, the Stuttgart area, are reflected in water levels in the Dewitt area 18 miles away. If the Peoria aquifer is a single one and no water infiltrates from the river, the data should have revealed interference effects between the several well fields. Since it does not reveal such effects, a nearby source of water seems to be the only tenable explanation. Thus, the internal evidence in the paper would lead one to deduce river infiltration.

From the data presented by the author it must be concluded that the apparent changes in water storage during floods at Peoria, Illinois, are real. These changes in storage are caused by the river water infiltrating to the aquifer during flood periods. I believe that further study will show that some water infiltrates even during periods of low water, despite a silted "impermeable" river bottom.

Max Suter (Author's comments, August 19, 1946)--The basic claim in both discussions is that infiltration from the river and the effect of pumpage are sufficient to explain the conditions found at Peoria, and that an explanation on the basis of compressibility is completely unnecessary.

I agree that the rise in water levels in the Peoria area could be satisfactorily explained on the basis of infiltration, but the fall in water levels cannot be explained in this way, and my paper attempts to find an explanation that will apply in the case both of rising and of receding water. This is possible only on the basis of compressibility. A few statements from the original paper must be emphasized.

The paper was limited to a discussion of the apparent changes in the quantity of water contained in the aquifer as a result of floods on the Illinois River. In such a short paper it was possible to mention only some of the results of our six years of investigation at Peoria, without including the data to prove our conclusions. It was claimed only that the river bottom is practically water-tight at pool stage and that infiltration may occur on flooded bottom land. It was claimed only that loading is of major importance, but is not the sole cause of the rise.

The reasons for considering the river bed water-tight at pool stage are as follows:

Extensive silting has occurred in the river bed, not only where it forms a lake, but also in the channel. During construction of the bridge piers of the new bridge it was found that the silt, two feet below the lake bottom, was very dry, and there were 20 feet of silt deposits. Dredging in the channel to depths of 25 feet had no influence on water levels in the wells. The temperature lag is about four to five months, even in wells close to the river, and this, as well as the irregular chemical variations in the ground and river water, can be due as much to the effects of rainfall as to river infiltration. These factors so far are not conclusive proof for either theory.

On the other hand, infiltration may occur on flooded land. Most of the agricultural bottom land tested showed, by the steel cylinder method, a measured infiltration rate of 4.75 to 20.0 inches in seven hours, which is higher than the infiltration rate of about three inches per day needed to cause the calculated increase in storage.

This was determined for the 1943 flood as follows: Calculated increase of 26,689 million gallons in 30 days gives an average of 890 million gallons per day. If infiltration increases with increase in area of flooded land, the highest inflow may be twice this amount, or 1780 mgpd = 5,340 acre feet per day. Since at the peak about 30 square miles were flooded, this gives as the rate of inflow 5,340 × 640/30 = 0.28 foot per day. This value must be considered only as an indication of the magnitude.

Nevertheless, it is believed that the actual amount of infiltration on flooded land was much smaller. It is just as logical to assume that less than this calculated amount penetrated as it is to assume that only this calculated amount and not the full measured capacity of infiltration occurred. Any such change in assumption must be based on another set of observations or reasonable deductions.

It is only fair to nature to assume that infiltration on flooded land is a function of the amount of land flooded and of the depth of flooding, but not of the rate of change in flooding. In simple terms, if there is infiltration on flooded land, this infiltration occurs as long as the land is flooded, no matter if the river rises or recedes. If we also assume that the infiltration is somewhat proportional to the area flooded, then the daily amount of infiltration must increase during the period of rising water and decrease in the same ratio during the disappearance of the flood.

Applying this simple principle to the facts as observed, it can be seen that the rise in water level may be caused by infiltration, but the lowering cannot be explained if infiltration occurs as long as any land is flooded, since the lowering starts when the river stage begins to fall, that is, at a time when the opportunity for recharge from flooded areas is near maximum.

This can also be seen by the following calculations: The pumpage at Peoria is remarkably uniform and seldom varies over ± five per cent. Long-term observations of the formation of the recession cones at Peoria show that there is an over-pumpage of about nine million gallons per day. We must have, then, an average natural inflow of about 75 million gallons per day which can easily come from rainfall over the large area (about 250 square miles) which is contributing from the northwest alone, according to the bedrock topography. In fact, an infiltration of six inches per year over the farm land of this area will furnish all the water needed at Peoria.

If the net gain over the difference between pumpage and natural inflow was due to infiltration from the flooded areas during the 30 days of rise in the river, and we assume a proportional infiltration during the 45 days it took the river to recede to pool stage, we get the following balances for the 1943 flood:

Rising water--30 days	Amounts in million gallons
Natural inflow 30 days × 75 mgd	2,250
Inflow from flooded area	26,968
Total inflow	29,218
Pumpage 30 × 84.3	2,529
Calculated net gain in storage	26,689
Receding river--45 days	
Natural inflow 45 days × 75 mgd	3,375
Inflow from flooded area	40,452
Total inflow	43,827
Pumpage 45 × 84.3	3,802
Calculated net gain in storage	40,025

The actual loss was 28,798 million gallons for the 90-day period, or 20,360 million gallons for the 45-day period. These figures cannot be brought into any equilibrium, no matter what factor of porosity or drainability is used.

There certainly is no reason why infiltration from flooded land and the natural inflow should suddenly stop when the crest of the flood is reached. The rise in the water levels, therefore, can not be attributed to infiltration from flooded land.

Neither can pumpage cause the recession. Not only is the loss during the recession greater than the pumpage, no matter what reasonable factor of specific yield is used, but it should also be borne in mind that if the uniform pumpage causes the recession in a basin, the rate of recession should be less at high water levels than at low levels. Actually, the rate of lowering is the greatest shortly after the crest has passed, and decreases with the lowering of the level. The lowering, therefore, cannot be due to pumpage.

How about the other possibilities for a loss of water? Evaporation can be disregarded, as the ground water is always at least ten feet below the ground surface. Outflow into the river is also negligible, as at periods when the ground water is high the river is also high, which causes the ground water to be below the level of river water.

Comparison with other rivers can not be made very easily, as the Illinois River is a very flat stream, having for a distance of 70 miles above Peoria to 160 miles below Peoria only an average fall of 1-1/8 in/mi, even during floods. As the losses in elevation are practically concentrated during low-water periods at the navigation locks and dams, this extremely flat river is also extremely highly silted.

It is true that the maps show the greatest rise in the center of the fields. There are several reasons for this. The maps are made from the observed points in the wells, and there are no wells in the river. Then, if under the river there should be the greatest influence from compression of the gravels, any water so lifted is free to move to the low spots and fill them. The ground water is connected under the river, as interferences are felt by our recording instruments from one side of the river to the other.

I agree with McGuinness and Kazmann that the specific yield and not the porosity should be used in the calculation. The porosity can be measured. The specific yield can be determined by drainability measurements or by well tests. Preliminary drainability tests gave drainabilities of from 20 to 28 per cent, but these tests are neither reliable nor standardized in procedure. Well tests that allow the calculation of the specific yield could not be made in Peoria, as there were always too many interferences from wells that could not be kept under control during the tests.

It is believed that the specific yield is not less than 20 per cent. Naturally we have no right to use a low value just to make it fit a convenient but evidently false theory concerning the origin and disposal of the water. Actually, it does not matter much what factor is used, as no value of it will explain the observed phenomena.

On the other hand, if we assume that compressibility of the gravel plays a major part, we get an explanation covering the whole period of flood. The differing behavior in the various fields can be understood if we rid ourselves of convenient concepts, such as that the artesian effect is never greater than one-to-one in respect of loading, or that tightly packed gravel is inelastic.

We are aware that the experiment discussed was on a small scale, and that further tests should be made before too much weight is given to its quantitative results. All the experiment showed was that compression can cause a rise in water level. It is hoped that in our prospective hydraulic laboratory better experiments can be conducted on this problem.

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COMPARISON OF LYSIMETER RUNOFF, INFILTRATION, AND PERCOLATION TO STREAM FLOW

L. L. Harrold

Abstract--Water control and water use in agriculture are currently receiving much attention. Agricultural practices which aid in putting more rain water into the soil are effective conservation measures. This water put into the soil cannot always thereafter be forgotten. In some sections of the country, part of the rain water taken up by the soil contributes to stream flow. When the moisture content of the soil is high, much of the water of infiltration percolates to water tables. Subsequently, the increases to water in zones of saturation are reflected in stream rises. Measurements of these phenomena for a wet period in March, 1945 are presented. For contrast, the records for a storm with practically no percolation or ground-water rises are also presented.

Stream runoff from watersheds in the Appalachian and other regions, even at flood-time, is often comprised of large quantities of seepage flow. HURSH [see "References" at end of paper, 1936] at the Appalachian Forest Experiment Station in North Carolina frequently observed stream-channel storm flow when very little surface storm flow was apparent. This runoff water which infiltrated into the soil surface and appeared as stream flow during the course of the storm he termed "subsurface storm flow." Rain water taken up by the soil as infiltration percolates to rather shallow water tables. Water in these zones of saturation flows laterally reaching the ground surface in spring flow or seep spots. Infiltrated water thus contributes to stream flow.

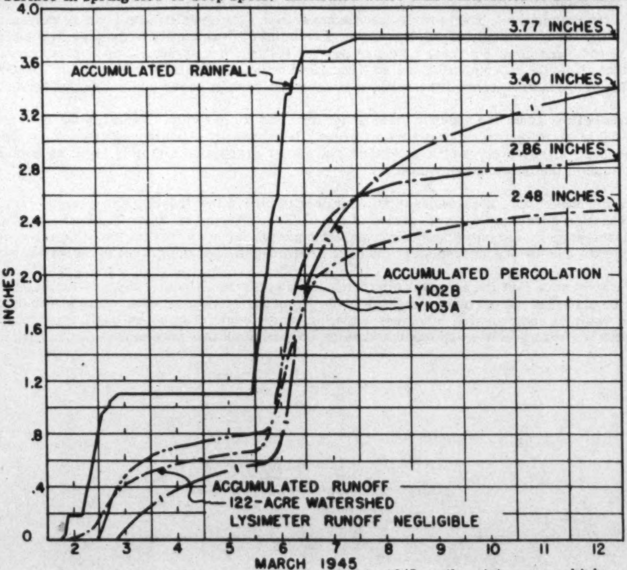

Fig. 1--Rainfall, runoff, and percolation, March, 1945; soil moisture very high

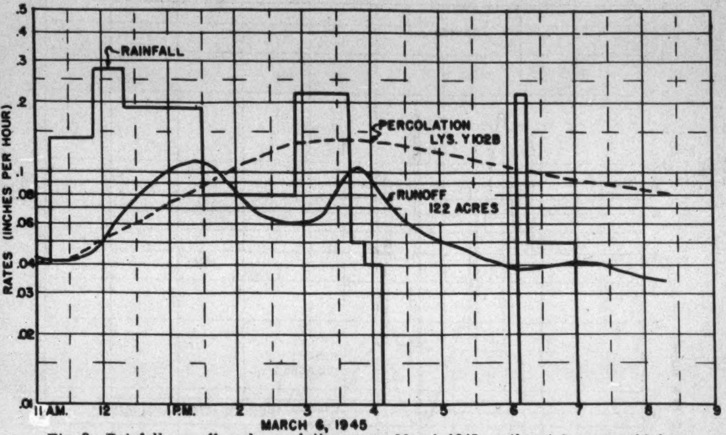

Fig. 2--Rainfall, runoff, and percolation rates, March,1945; soil moisture very high

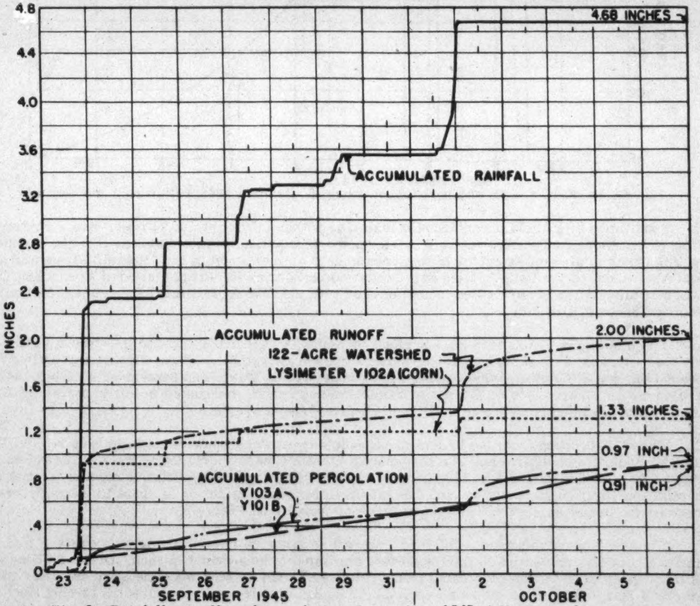

Fig. 3--Rainfall, runoff, and percolation, September, 1945, following a dry summer

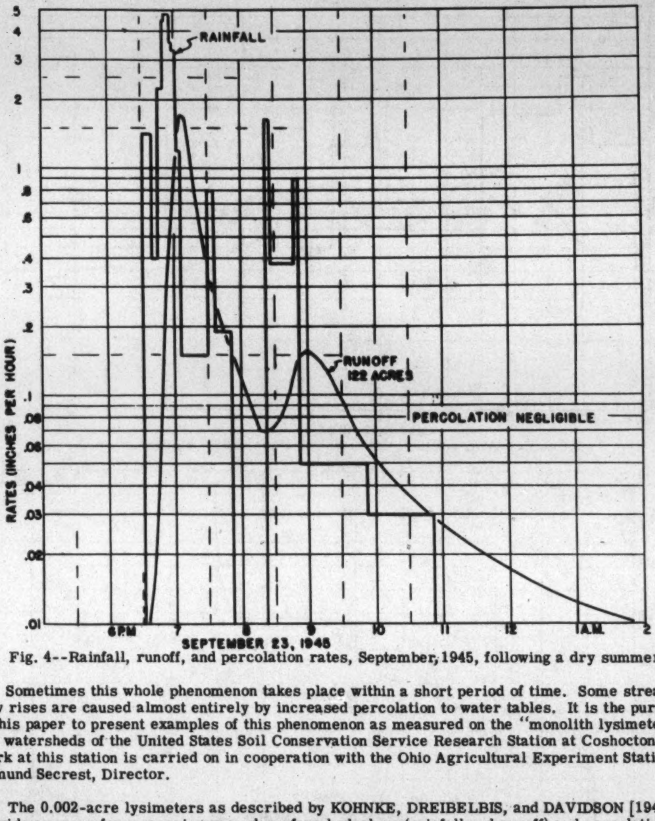

Fig. 4--Rainfall, runoff, and percolation rates, September, 1945, following a dry summer

Sometimes this whole phenomenon takes place within a short period of time. Some stream flow rises are caused almost entirely by increased percolation to water tables. It is the purpose of this paper to present examples of this phenomenon as measured on the "monolith lysimeters" and watersheds of the United States Soil Conservation Service Research Station at Coshocton, Ohio. Work at this station is carried on in cooperation with the Ohio Agricultural Experiment Station, Edmund Secrest, Director.

The 0.002-acre lysimeters as described by KOHNKE, DREIBELBIS, and DAVIDSON [1940] provide a means for measuring ground-surface hydrology (rainfall and runoff) and percolation at the 8-foot depth. Graphs of these phenomena for periods in March and September-October, 1945, are shown on Figures 1 to 4. Graphs of rainfall minus runoff, designated in this paper as infiltration, can be obtained from the rainfall and lysimeter-runoff graphs.

Water percolating from the bottom of the 8-foot lysimeters contributes largely to stream flow through underground channels. The response of stream flow to increased percolation is shown on Figure 1. Figures 1 and 3 may also be used to make time-lag and quantitative studies relating to rainfall, infiltration, percolation, and stream flow. Note the lag period of about 12 hours between rainfall and runoff on Figure 1 and the absence of such lag on Figure 3.

The graph of accumulated rainfall on Figure 1 is assumed to be infiltration because actual surface runoff as measured on the lysimeters amounted to less than 0.05 inch. Of the 3.77 inches of infiltration, 3.40 inches percolated from lysimeter Y102B by March 12, the sixth day after the storm of March 6. During the same period 2.48 inches of water was measured as stream flow from a 122-acre watershed. Much of this stream flow must have come from underground sources because the plots showed practically no surface runoff. Note how closely the mass curves of percolation and runoff agree. Also it is interesting to note the general lag between infiltration and percolation and stream flow.

The 122-acre watershed for the March storm was about 80 per cent in grass and woods, 10 per cent in small grain, and 10 per cent in roads, buildings, barn lots, and other miscellaneous slowly permeable areas. The surface of the lysimeter was in grass.

Rates of infiltration (same as rainfall in this case) and percolation for the lysimeters and the runoff from the 122-acre watersheds for March 6, are shown on Figure 2. Runoff from the lysimeters was negligible. An examination of these rate curves shows that much of the runoff in the stream came from percolation water. The sharper fluctuations of the stream-flow graph were caused by surface flow from roads, buildings, and other relatively impervious areas. The percolation rate exceeded the stream-flow rate (Fig. 2) and the total percolation was greater than the total stream flow (Fig. 1). It seems reasonable, therefore, to conclude that some of the water of percolation contributed to ground-water storage--not all of it went to stream flow. The fact that the percolation rates and amounts late in the storm remained greater than corresponding stream flow, also tends to substantiate this conclusion. Unfortunately, there are no records of ground-water levels at this station during the period.

Similar data for the storm of September 23 are shown on Figures 3 and 4. The 122-acre watershed for the September storm was about 70 per cent in grass and woods, 10 per cent in small grain stubble, 10 per cent in corn, and 10 per cent in miscellaneous slowly permeable areas. The surface of lysimeters 102 and 103 was in corn and that for Y101 was in grass. Stream flow from the 122-acre watershed amounted to 2.0 inches--much of it was surface runoff. Note the rapid response of runoff to rainfall (Fig. 3) compared with the slower response of stream flow for March (Fig. 1). Also compare the magnitude of the flood peaks for the 122-acre drainage area (Figs. 2 and 4). The flood peak for September 23, comprised of surface flow in large quantities was about 15 times greater than the March 6 storm, comprised mostly of seepage flow. These differences are reasonable.

Attention is called to the comparison of lysimeter runoff with stream flow for the storm of September 23 (Fig. 3). Stream flow totaled 2 inches--which is greater than the total surface runoff for the corn lysimeter (Y102A). Yet, corn land in the 122-acre area comprised only about 10 per cent of the watershed area. If the surface flow from the grain stubble land (10 per cent of the area) was one-half that for corn land, that from the miscellaneous slowly permeable areas (10 per cent of the area) was 100 per cent, and that from grass and woodland (70 per cent of the area) was 0.03 inch, the combined surface flow would be as follows:

Corn land surface flow 1.33 inches at 10 per cent of area = 0.13 inch
Grain stubble surface flow 0.66 inch at 10 per cent of area = 0.07 inch
Misc. areas surface flow 4.68 inches at 10 per cent of area = 0.47 inch
Grass and woods surface flow 0.03 inch at 70 per cent of area = 0.02 inch
Total surface flow = 0.69 inch
Total lysimeter percolation = 0.95 inch
Total = 1.64 inches

Apparently there was considerably more surface flow from the 122-acre watershed than can be accounted for from the lysimeter data, or there were considerable quantities of rapid storm seepage flow from shallow water tables. From the appearance of the rate graphs (Fig. 4), the more logical conclusion would favor the former possibility--more surface flow.

It is interesting to note that 5 inches of rain fell in September before percolation began. Only about one inch of percolation resulted from the 4.68 inches of rainfall after percolation started (Fig. 3). Apparently, much of the 10 inches of rainfall in September was taken up by soil moisture storage. By September 8, soil-moisture storage had almost been reduced to the wilting point. A large volume of unfilled pores was available to take up water before the field capacity was reached. Records show that the water in the 0 to 40-inch profile increased from 4.5 inches to about 10 inches in 25 days. This is a 5.5-inch addition to moisture stored in the top 40 inches. Four inches of this increase occurred before percolation started. As 5 inches of rain fell in this initial period, water in excess of the four inches mentioned above went into soil depths below the 40 inches.

In agricultural hydrology, much stress is placed on the problem of water control. For the well-drained soils on sloping land of the Appalachian region the problem is to reduce as much as possible the quantity of water flowing over the land surface. This means that the water must enter the soil, or infiltrate. On well-drained profiles, this does not introduce other problems. There, the soil water exceeding field capacity soon percolates downward allowing the soil to take up air. On poorly drained soils, increased infiltration would, at times, aggravate a water-logged condition, thus contributing to decreased crop yield. It is for well-drained profiles that data are herein presented.

Farm practices which aid infiltration and reduce surface runoff are expected to be most beneficial in reducing floods like that of September 23. Studies now in process are being directed towards evaluating the magnitude of the effect of agricultural practices on such floods as well as all others.

This paper is presented to serve as a forerunner of later papers giving greater detail on the rain-water disposal factors. Many storm types with different soil moisture, vegetal cover, and tillage treatments will be covered. Free discussion of these problems is desirable in the interests of valuable developments that appear imminent.

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Transaction, American Geophysical Union Volume 28, Number 3 June 1947

GRADE CHANGES IN CHERRY CREEK, DENVER

E. W. Lane

Abstract--Some interesting changes of stream gradient have taken place in Cherry Creek in Denver, Colorado, as a result of structures built for its control. In straightening the stream, its course was shortened and narrowed and the banks were paved, thus increasing the velocity. Consequent scouring has degraded the slope, thereby tending to undermine structures and to produce other phenomena which are described.

Cherry Creek joins the Platte River in the City of Denver, Colorado. In the section under consideration it was, before improvement, a typical plains stream with a flat, rapidly shifting bed, low banks, and a slope of 30 feet per mile. Much of the lower four-mile reach of the stream has been controlled for many years by confining it in a narrow channel with high retaining walls on each side and cross walls or sills at intervals across the bottom. Above this stretch the stream flowed in a valley of moderate width with a winding course and shifting banks. About 13 years ago, levees paved with riprap were started on both banks to restrain wanderings of the stream, and to protect adjacent property, confining the stream to a comparatively straight course with a width about equal to that of the low water channel. This shortened the course of the stream somewhat, and confined flood flows to a narrower channel. The result was a flattening of the gradient beginning at the lower end of the leveed section, which caused a lowering of the stream bed for some distance upstream. This lowering threatened to undermine the bridge at Colorado Boulevard, and to expose a pipe line crossing at that point. The present condition of this bridge, with the upper part of the footings exposed, is shown in Figure 1. Several small dams were constructed to prevent further lowering. Considerable degrading has resulted below these dams, as shown in the profile given in Figure 2. Just below one of those dams, erosion of the bed of about six feet has occurred and at the dam upstream the lowering has been about nine feet as shown in Figure 3. Both structures are protected by great quantities of large-size riprap on the bed and banks. The highest of these dams has been in service about six years. Between these two dams the average slope of the stream has been lowered from about 30 to about 24 feet per mile. The dams further upstream have been constructed more recently and at these only slight degradation has occurred.

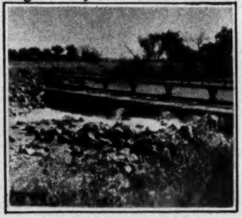

Fig. 1--Footings of Colorado Boulevard Bridge exposed by degradation of Cherry Creek Bed

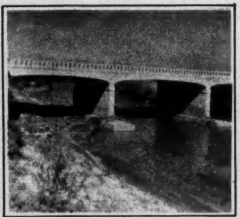

Fig. 2--Effect of degradation below dam on Cherry Creek

The Kenwood Dam is located several miles farther up the valley with a concrete conduit or tunnel through it, forming a retarding basin to limit the flood flow to a magnitude which can be carried safely by the channel downstream. During the summer of 1945, a flood occurred which caused a small amount of storage in this retarding basin. The author inspected the effect of this basin on the stream gradient a short time after the flood. At that time there appeared to have been sediment deposits in the basin to a depth of about seven feet, and below the dam, a degradation of about four feet. The basin had been empty for some time and the stream had begun to cut into the deposits in the reservoir. The degradation below the dam probably had also been reduced.

From the changes which have taken place in Cherry Creek, it may be concluded that when engineers propose to confine or straighten a stream of this nature, the possibility that it will degrade its bottom should be considered. If a retarding basin is built on a stream of this type, the possibility of rapid degradation below the dam at times of flood should be considered in the design of the outlet works. There is also the possibility that after the flood the degraded section may not only be refilled to its former level, but may even refill to a

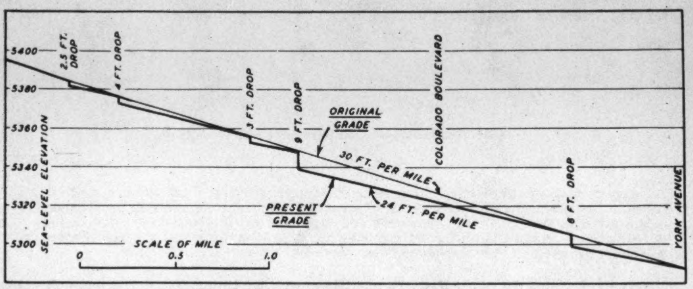

Fig. 3--Profile of Cherry Creek, Denver

higher level. A condition tending to produce this effect is a deep, narrow basin with steep gradient above the dam. During a flood a thick layer of sediment is deposited on the stream bottom in this basin. This sediment will be largely washed out when the basin is empty, as the stream cuts into this deposit. Another condition favorable to this effect is a relatively resistant bed downstream from the dam on which there will be little degradation. Under these conditions the stream bed may aggrade for a period after the flood, as the stream in the retarding basin carries downstream the sediment that was deposited in the basin during the flood. This will probably be followed by a period of degradation through this aggraded deposit, as the stream gradually restores its original grade.

The writer desires to acknowledge the assistance of J. N. Bradley and J. E. Warnock in collecting the data used herein. The writer alone is responsible for the conclusions drawn from it.

U. S. Bureau of Reclamation,
Denver, Colorado

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FREQUENCY AND SEASONAL DISTRIBUTION OF PRECIPITATION OVER LARGE AREAS

Ray K. Linsley, Jr.

Abstract--The need for charts showing the frequency of precipitation in various amounts over large areas and its distribution throughout the year frequently arises in hydrologic problems. This paper presents a method, applicable in regions where topography is a controlling factor in areal distribution of precipitation, for developing such charts with a minimum of effort. The procedure is predicated on the assumption that storm patterns are similar to the mean annual precipitation pattern. Charts for selected West Coast areas are included.

Introduction--The United States Weather Bureau recently inaugurated a program of quantitative precipitation forecasting as a special feature of its general weather service. Techniques for preparing such forecasts are at present very limited. It is therefore of considerable value to the forecasters to have some knowledge of the frequency and seasonal distribution of precipitation to supplement available forecasting techniques and to prevent issuance of forecasts of amounts far beyond the usual range of occurrence without a thorough review of the facts leading to the forecast.

The quantitative precipitation forecasts are issued in terms of average depth in inches over specified zones and for periods varying from six to 24 hours. The zones are each approximately 10,000 square miles in area, this having been found to be the optimum size for such forecasts [see "Reference" at end of paper, SHOWALTER, 1944]. The zones are selected such that they include in so far as possible only meteorologically homogeneous areas, although practical operation requirements are necessarily considered in this selection. Figure 1 shows zones used within the San Francisco forecast district.

In reviewing the problem it is obvious that a single station or the average of two or three stations will not adequately indicate the true average precipitation in any zone located in the mountainous terrain under consideration. On the other hand, the computation of daily mean precipitation for a zone by averaging daily amounts for all stations in the zone over a 35-year period of record would be a tremendous task. Because of the non-uniform distribution of stations with elevation and the scarcity of stations during the earlier years such a procedure would also be far from reliable.

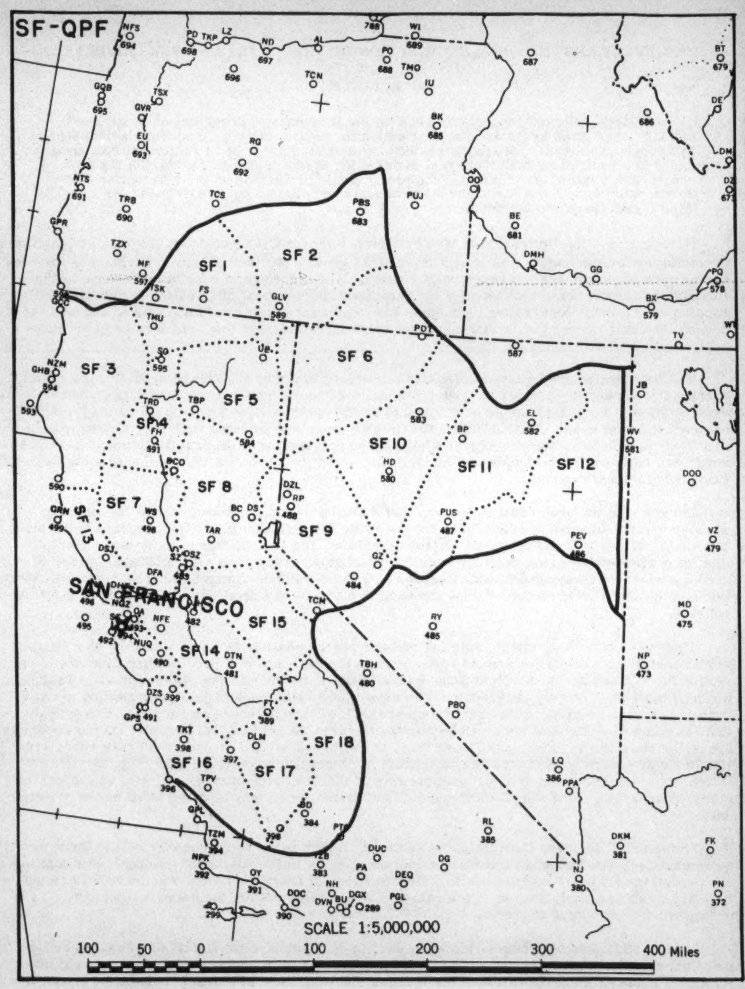
Theory--A relatively simple solution and one which seems to be as satisfactory as a limited arithmetic average of station amounts was found in the expression of precipitation amounts in per cent of the average annual precipitation. Precipitation over the various zones of the San Francisco forecast district is largely orographic. The topography which induces this precipitation is unchanging and can be expected to exert substantially the same influence on each storm provided that (1) inflow directions of the storms crossing the area do not vary excessively; (2) the air-mass characteristics are reasonably the same from storm to storm; and (3) the area under consideration is small enough so that variation in latitude of storm tracks does not affect the distribution within the zone. Other factors, for example rate of inflow of moisture-bearing air, will affect the storm distribution. However, the three conditions listed above may be considered as the principle ones.

The zones of northern California and southern Oregon conform reasonably well to these requirements. Storm-inflow directions are confined largely to the southwest quadrant. Air masses are predominately polar maritime with a limited range of characteristics, and the zones are sufficiently small that variations in storm path do not seriously distort the relative distribution of precipitation from storm to storm.

Areal distribution of precipitation expressed in per cent of mean annual was found to be far more uniform than the distribution of precipitation expressed in inches depth. In preparing river forecasts at the Sacramento Office of the Weather Bureau, maps of storm precipitation in per cent of mean annual are plotted and the average percentage estimated for each basin. This average percentage multiplied by the mean annual precipitation over the portion of the basin below the snow

line provides a reliable estimate of the average rainfall in the runnoff zone.

Obviously this indirect approach cannot yield perfect results. The variations in storm track and inflow direction have already been suggested as possible sources of error. In the area under study, variation in inflow direction is small and the effect of variation in storm track can be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SAN FRANCISCO
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100
50
0
100
200
300
400 Miles

Fig. 1--Map showing zones used within the San Francisco forecast district

reduced by restricting the size of the area to which the method is applied, or more specifically limiting its linear dimension normal to the average storm tracks. The method does not apply to the summer thunderstorms which occur in the mountain regions. Thunderstorm rainfall is, however, a negligible portion of the total annual precipitation and does not pose any serious objection to the use of this procedure. The passage of an intense cold front with very unstable air is sometimes accompanied by intense precipitation set off by the first lifting action of the foothills. Under such conditions very heavy rainfall may occur in the foothills with precipitation currently decreasing with elevation, in contrast to the average annual pattern. Such occurrences are relatively rare and it is not believed that they introduce serious error in the computations which have been made on precipitation frequency, although the use of an isopercental map for single storm analysis is not feasible for such storms.

Method of development--The following procedure was used to develop the charts of Figure 2: (1) The number of occurrences of daily precipitation in intervals from 0.01 to 0.10, 0.11 to 0.25, 0.26 to 0.50, 0.51 to 1.00, 1.01 to 2.00, and by two-inch increments above 2.01 inches were tallied for selected stations having long records. The number of occurrences in each interval was determined for three periods each month; 1st to 10th, 11th to 20th, and 21st to end of month. (2) The per cent of occurrences above the lower limit of each range was computed by dividing the total tally above that limit by the total number of days in the period (eight, ten, or eleven multiplied by the number of years of record). (3) A duration curve (per cent of days above each amount versus per cent mean annual precipitation) was plotted for each of the 36 periods for every station. From these curves a summary of durations for precipitation percentages equal to or exceeding 0.01, 0.10, 0.25, 0.50, 1.00, 2.00 inches, etc., of average precipitation over the zone was compiled for each station. (4) Average durations for each zone were computed by averaging station durations.

The resulting charts for 12 zones in California and Oregon are shown in Figure 2. Before plotting the charts, the data were smoothed by using a three-period moving average. In drawing the curves only negligible smoothing of the plotted data was introduced. The average deviation of the plotted points from the smoothed curves is approximately one per cent. The short interval (ten days) was selected because of the importance of showing the variation in frequencies within calendar months, as, for example, the abrupt decrease in frequency during the latter portion of February in Zone SF1.

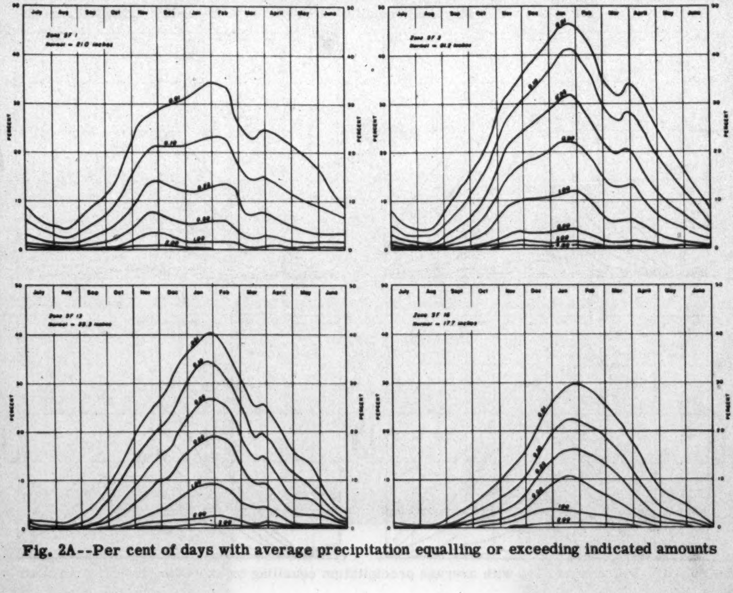

Fig. 2A--Per cent of days with average precipitation equalling or exceeding indicated amounts

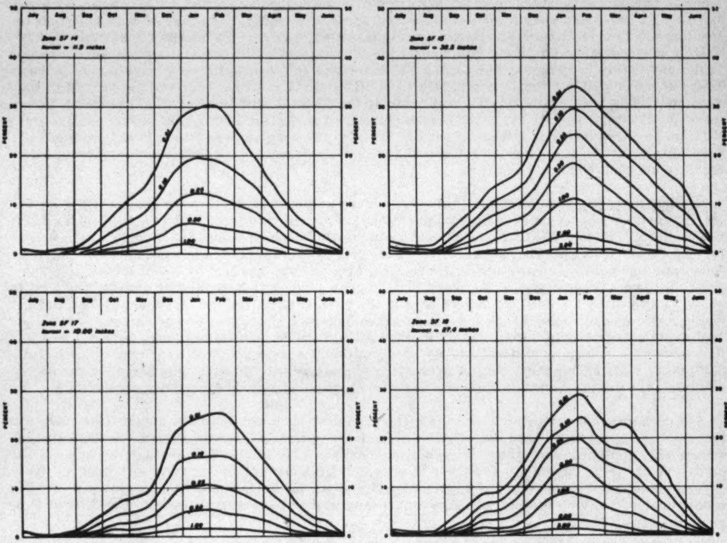

Fig. 2B--Per cent of days with average precipitation equalling or exceeding indicated amounts

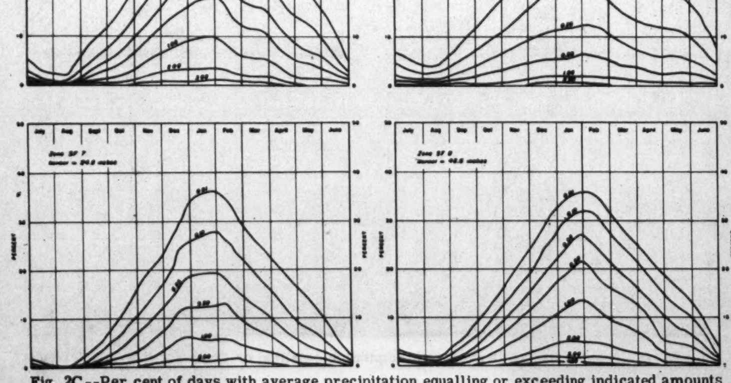

Fig. 2C--Per cent of days with average precipitation equalling or exceeding indicated amounts

Interpretation--No attempt has been made to extrapolate the record or to develop curves for predicting probable frequency of occurrence. The duration percentages shown are the observed values subject to the smoothing procedure described earlier. On the average, 35 years of record were used for these charts. Hence, one occurrence in 35 ten-day periods is about equal to 0.3 per cent, which is about the lowest value shown on the curves. The curves may thus be interpreted as indicating the frequency distribution as observed during the period of record. A value of 30 per cent on a given date indicates rain equal to or exceeding indicated amount occurred in three out of ten years on the average. An average of 30 per cent for a month indicates that the average month has had approximately nine days with rain in the indicated amount.

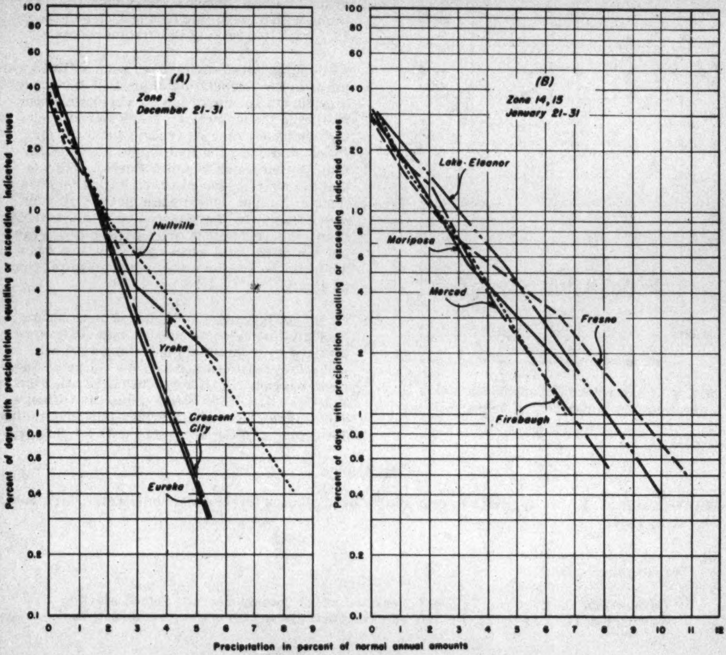

Fig. 3--Comparison of station-duration curves

Further evidence of the practicability of using per cent of mean annual as a common denominator is given in Figures 3 and 4. Figure 3 displays two groups of station duration curves for different periods and zones. It will be noted that in each case the several curves are very similar. In each case the entire period of record available for each station was used, and the periods, therefore, differ slightly from station to station. The use of ten-day periods makes it possible that extreme amounts occurring within any period at one station may be recorded in an adjacent time period as a result of varying times of observations. These facts account, in part, for differences between stations for the less frequent amounts. The most exposed coastal stations (Eureka and Crescent City, Fig. 3A) and the higher elevation stations (Lake Eleanor, Fig. 3B) tend to show more frequent occurrences of very light rains than do the more sheltered valley stations. This is, of course, what would be expected since the exposed stations are more likely to get light showers when minor storms cross the area. It is to be noted that the annual normals at Fresno, Firebaugh and Lake Eleanor are 9.3, 7.6, and 42.4 inches, respectively. The curves of Figure 3B would be many times more divergent if plotted in terms of rainfall depths.

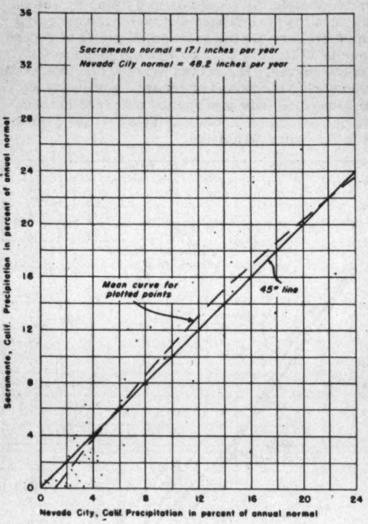

Fig. 4--Comparison of concurrent storm precipitation in per cent of annual normal

Figure 4 displays the relation between two stations of Zone 8 by plotting corresponding storm amounts in per cent normal. The resulting mean relation is not far from a 45-degree line through the origin indicating close agreement between the stations when amounts are expressed in per cent of mean annual precipitation. Actual precipitation amounts at the two stations differ considerably in magnitude, but a graph of actual amounts would show equal correlation with a mean line having a slope near to 17.1/48.2 (the ratio of the station normals).

Conclusion--A method has been outlined which permits the computation of areal frequency with a moderate amount of labor. No claim to perfection in the indirect approach can be made, but the evidence indicates reasonable accuracy. Other studies by the Hydrologic Services Section, United States Weather Bureau, indicate that the average annual precipitation is a practicable common denominator in the Columbia River Basin and the Wasatch Mountain area of Utah. Where summer precipitation is a large portion of the total annual amounts, it may be desirable to use the mean winter precipitation as a base.

Acknowledgments--Values of mean annual precipitation by zones used in this study were obtained by planimetering the mean annual isohyetal maps developed by the Corps of Engieers, Sacramento District Office. E. H. Fletcher and F. E. Hug of the Weather Bureau Office, Sacramento, were of material assistance in the development of the necessary data for this paper.

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Washington 25, D. C.

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GEOLOGIC MODELS MADE FROM GRANULAR MATERIALS

L. L. Nettleton and Thomas A. Elkins

Abstract--This paper describes geologic models made with high density powders overlying a lower density fluid. Movement is induced by gravitational forces only and, in most of the models, "deposition" was effected contemporaneously with "deformation." Granular materials were selected because they are particularly adapted to show faulting. Models were made to show salt-dome structures, and thrust and tension faults. Some of the thrust structures, in particular, closely resemble known geologic structures.

The concept of a Mohr diagram for sediments and other geologic materials similar to that for the powder mixtures is used in evaluating the model ratios in terms of measured properties of these mixtures and of known or inferred values for the properties of rocks involved in natural geologic structures.

Introduction--It may interest the reader of this paper to be told that the work is described here in approximately the chronological order in which it was performed. Because of the exigencies of war work, the course followed was close to the reverse of the logical order which would have been followed in normal times, in that the final choice of dry powders as model materials was made first on an intuitive basis (principally because of their extreme weakness) and then the choice was later justified by mathematical and dimensional analysis.

Previous work--The primary object of these experiments was to obtain an understanding of faulting and, in particular, of faulting around salt domes, including down-dropped grabens over the centers of domes, which have become known in recent years to be a common condition in salt dome tectonics. Among the first domes where such faulting became well known was Conroe, where a series of east-west faults forming a graben across the center of the dome is shown by the structure maps based on the drilling [see "References" at end of paper, MICHAUX, 1936]. A paper by WALLACE [1944] contains data from electric logs from drilling of deep-seated domes in the Louisiana Gulf Coastal area and shows many instances of faulting in which the side of the fault toward the center of the dome is down-dropped.

In the published work on geologic models, there is very little that seems to be pertinent to the problem. LINK [1930] reported some early experiments on the intrusion of solid and fluid materials through an overburden simulating sediments. These showed cracks and faults of various kinds but none that were at all suggestive of grabens over the uplift.

KOENIGSBERGER [1924] considered the strength and time requirements for geologic models and showed that very weak materials should be used, and included some results of simple compression-box tests made with such materials.

CLOOS [1930 a and b, 1931] carried out a very interesting series of experiments with a rather thin mud as the model material and reproduced graben-like forms by withdrawing one of two thin sheets underlying the material, so that a zone of tension was formed over the edge of the sheet. The pictures in Cloos' reports are strikingly similar to many geologic forms as shown by exposures and cross sections, and suggest a means of simulating a zone of tension which appears to be a necessary condition for graben formation.

Earlier fluid models [NETTLETON, 1934, 1943] of salt-dome forms did not produce faulting. Furthermore, the fluid models which have been made all had vertical and horizontal dimensions of the same order of magnitude; whereas, to simulate properly even a small portion of a salt-dome area, it is necessary that the horizontal dimensions be at least several times the vertical.

Consideration was given to using as an overburden, material similar to that used by Cloos, and some preliminary experiments were made with muds made from various drilling-mud weighting materials. The gel strength of such muds and clays is an important consideration and varies widely in different materials. It seems probable that Cloos empirically had found a reasonable satisfactory material without appreciating the importance of the gel strength. In the tests we made, when the muds were weak enough to form model materials at the scale desired, they were so fluid that no strain lines or actual faults were observed. Another difficulty arose when it was attempted to use such muds over syrup, which is a very desirable fluid underlayer, as it is transparent and its viscosity can be easily controlled. When a clay mud is placed on top of the syrup as an overburden, the syrup goes into solution in the water of the overlying clay and destroys the gel, so that the clay particles settle out of the water quite completely, thereby destroying the desirable properties of the mud. This difficulty could be avoided at the expense of loss of transparency of the underlayer by using an asphalt instead of syrup. The above is as far as the experiments with clays as model materials were carried out.

Dry powders as model materials--The general properties of a dry powder make it attractive as a material for models, particularly those designed to show faulting. The manner in which a pile of powder falls and breaks when disturbed or when the base on which it rests is distorted results in many features which are superficially similar to geologic deformations. Therefore, it was decided to attempt some experiments using a dry powder as the heavy overburden with corn syrup of suitable viscosity as the fluid underlayer. This required that, if density differences and gravitational forces are to motivate the deformation, the bulk density of the powder must be substantially greater than that of the syrup.

After some preliminary testing of various materials, two were selected which appear to have properties suitable for use in models. These are ordinary Baroid (drilling-mud weighting material) and steel shot. The Baroid is, mostly, finely ground barium sulphate. The steel shot is prepared for sand blasting and consists of fine, approximately spherical, steel grains, apparently made by spraying molten metal. The size used (Pittsburgh Crushed Steel Company, no. 40) is approximately 0.02 inch in diameter. All of the tests described below were carried out in a box approximately 29 inches square and four inches deep (see Fig. 1).

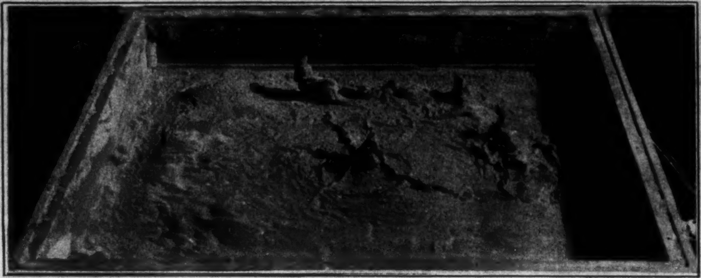

Fig. 1--Photograph of model box

Salt dome models--In the first tests, an initial dome was made by simply making a mound in the syrup and chilling it with dry ice to hold its shape while the box was filled with Baroid. It was found, however, that even if the mound were large and half as high as the depth of the box no movement whatever took place, even in several days' time. This seemed to indicate that the model material, that is, the Baroid, was much too strong for the scale of the model.

The next experiments were made with a series of mixtures of various proportions of shot and Baroid but generally in the range of 1/8 to 1/3 Baroid by volume. Domes were started either by making an initial mound on the syrup or, somewhat more conveniently, by simply making a depression in the surface of the powder overburden. It was soon found that if the initial dome were covered by an overburden exceeding a certain thickness, the material became completely stable and no further flow occurred. However, by adding powder to the box so that a comparatively thin layer covered the top of the rising dome at all times, the dome would continue to rise indefinitely and would flow out over the surface if the addition of powder were slowed up or stopped. The critical overburden thickness which would stop a dome uplift was not very accurately determined but appears to be between 1/2 and 3/4 inch.

It seems probable that this concept of a critical overburden may be an important factor in salt-dome mechanics. If we carry the analogy to salt domes in nature, it would appear that when the rate of deposition exceeds the rate of salt uplift by a sufficient amount so that a dome becomes buried by more than the critical overburden, it may become stationary and no longer follow up through the increasing thickness of overlying sediments. At the same time, a dome which happened to be moving a little faster would continue rising, keeping its top at or near the surface of the sediments being deposited. This might account for situations such as we find in the Gulf Coast, where we have, for example, Moss Bluff and Hankamer, a shallow and a deep dome side by side.

The configuration of the syrup involved in an uplift was studied by simply mixing powdered dry ice with the powder overburden, thereby chilling the mass of powder and the underlying syrup and freezing the configuration of the syrup and then removing the powder. Uplifts formed in this way are shown in Figure 1 and in the steroscopic pictures described in the next section. In all of the domes formed by simple gravitational flowage under a powder overburden, there was no indication of any down-dropped segments over the domes.

Models combining structural deformation with dome uplifts--While carrying out experiments with domes, a test was made with the powdered material loaded more heavily on one side of the box than on the other. This caused some flowage of the underlying syrup and displacement away from the loaded area, so that tension faults were formed near the more heavily loaded edge of the box. This led to a series of experiments on the use of the powdered material to simulate more ordinary structural movement involving tensile and compressive forces. It was found that suitable movement in the powder overburden could be induced more conveniently by simply tilting the box.

Experiments were made to try to get a combination of a dome-like uplift and graben-like faulting by inducing the graben formation by the expedient of covering only part of the bottom of the box with syrup before loading it with the overburden. If the box is then tilted, a zone of tension occurs in the region of the overburden above the edge of the syrup (see Fig. 2). At the same time, there is some tendency for the syrup to rise into the tension faults occurring near the edge. An experiment of this kind is shown by the stereoscopic photographs in Figures 3 and 4.

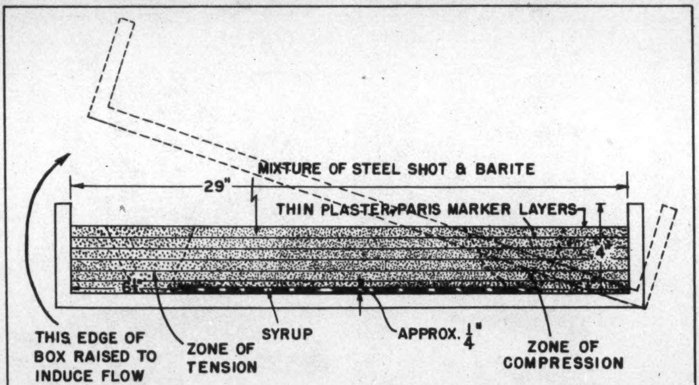
MIXTURE OF STEEL SHOT & BARITE
29"
THIN PLASTER-PARIS MARKER LAYERS
4"
6½"
THIS EDGE OF BOX RAISED TO INDUCE FLOW
ZONE OF TENSION
SYRUP
APPROX. ¼"
ZONE OF COMPRESSION

Fig. 2--Section of box, showing formation of tension and compression zones by tilting

Figures 3a and 3b show the surface of the powder, with marked faulting occurring towards the right-hand side. The dome which had been induced by an initial mound on the syrup rose as successive layers of powder were applied until it pierced the overburden (the small mound of powder on the surface had to be added to keep it from flowing out over the powder surface). The graben-like faults at the right are over the edge of the syrup but apparently did not extend far enough away from the edge to make a graben over the dome. Figures 4a and 4b show the surface of the syrup after it was frozen with dry ice and the powder overburden removed. The crenulations in the surface of the syrup near the right-hand edge lie directly under the zone of faulting and show the syrup had started to flow upward into the tension region in the overburden. (An interesting stereoscopic trick was tried with the two pairs of pictures for Figures 3 and 4. By carefully registering the negatives for Figures 3a and 4a, which were taken from the same point, and making a print through both negatives at once and doing the same with Figures 3b and 4b, a new stereoscopic pair was made, showing both the surfaces, that is, the top of powder and the top of syrup. By a little stereoscopic training, it is possible to see a three-dimensional picture with the powder surface appearing as if on a transparency above the syrup surface.) A similar set of stereoscopic pairs for another test is shown in Figures 5a and 5b for the powder surface and in Figures 6a and 6b for the underlying syrup. In Figures 3 to 6, the right-hand edge of the box was raised in all cases so that the force component was toward the left.

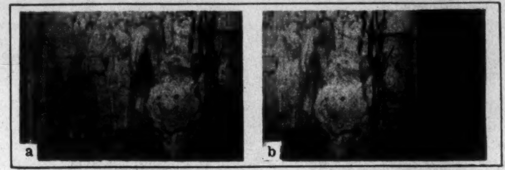

Fig. 3--Top of powder surface showing domal uplifts and faults

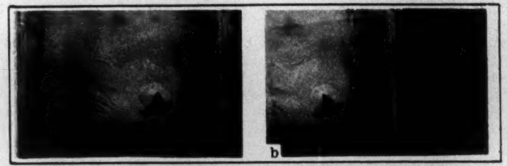

Fig. 4--Syrup surface under powder of Figure 3 (note dome and crenulations under faulted region)

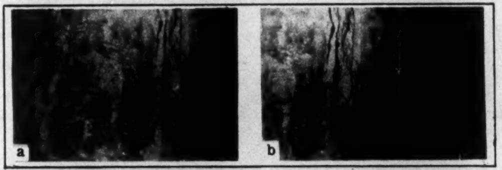

Fig. 5--Top of powder surface showing faults

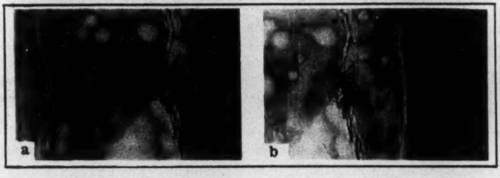

Fig. 6--Syrup surface under powder of Figure 5 (note overthrust segment at left side of 6a); white blotches are frost areas from dry-ice cooling

Structural deformation models--The experiments to be described below are a series made without regard to the salt-dome problem and as a diversion into the field of models which have been made by many geologists to simulate geologic movements and resulting structure. The purpose was to make what appears to be a new type of geologic model, in that "deposition" occurs simultaneously with "deformation" and only gravitational forces are applied. Further, the effects of varying the physical properties of the powder on the model ratios and on the resulting deformation were studied.

The technique of making these models is generally illustrated by Figure 2 and includes the following steps:

(1) The syrup (or asphalt) layer was placed across approximately the central half of the box, leaving the right- and left-hand sides of the box bare.

(2) The syrup and bare parts of the box were covered with a layer of powdered material 1/2 to 3/4 inch thick. The top of the layer was covered with a thin layer of plaster of Paris (dry powder) to act as a marker.

(3) One side of the box was lifted up so that there was a horizontal force component (toward the right, see Fig. 2) away from the bare area along the left side of the box and toward the similar parallel bare area along the right side of the box. The amount of tilt was not very definitely controlled. The angle of tilt varied from 10° to a maximum of about 30° in a few cases.

(4) After some horizontal movement of the first layer had taken place, a second layer was added and covered with another thin layer of dry plaster of Paris. This process was repeated with continual deformation and intermittent deposition until five or six layers had been formed and the box substantially filled. In most of the tests the angle of tilt was increased as the material was added. This was necessary to overcome the compressional resistance of the thicker section of powder in the thrust zone.

(5) At the stage when the deformation was to be terminated, the edge of the box was let down to make it horizontal again. Two thin sheet-iron partitions, about 4 inches apart and in planes corresponding to the section of Figure 2, were pushed down through the powder and syrup to the bottom of the box. The section between these strips was saturated with water, which serves to cement the powder.

(6) After two to four days, the dry powdered material in the outer parts of the box was removed and the cemented section between the two partitions carefully lifted out after it was clamped between supporting wood strips. A slice was cut off with a hack-saw and the section then photographed. Figures 7 to 13 were made in this way. For the last section (see Fig. 14), a much more satisfactory technique was developed. After removing the powder and the sheet-iron plates and leaving the section to be removed standing by itself in the box, the top and sides of this section were covered with a moderately stiff plaster of Paris (wet), much like frosting a cake. The cemented section can then be removed easily, the bottom cleaned off and the ends also covered, tc encase completely the model with plaster. The section may now be cut quite easily by simply sawing through the cemented powder and its plaster "frosting." This is particularly useful for powder mixtures which do not form a firm cement.

Figures 7 and 8 show the result of presumably identical experiments carried out with the overburden consisting of a mixture of approximately three parts (by volume) of iron shot to one part Baroid. Note that the graben-like faulting at the left end is quite sharp and that there is pronounced thickening of the section within the graben. The different layers can be followed by carefully counting down from the top. Such counting will show that the two bottom layers have disappeared completely from the area of the graben. Figures 9 and 10 are made with the overburden consisting of iron shot only, without any Baroid. The marked differences in structure are caused by the differences in the properties of the materials used.

Figure 11 was made with Baroid only. Figure 12 was made with a powder containing 75 per cent Baroid and 25 per cent (by volume) of Portland cement. The density of this mixture is somewhat lower than that of the pure Baroid powder, but other properties are similar (see Table 1). Figure 13 was made with the same powder but with asphaltum oil instead of syrup. (The asphalt was used initally to avoid the tendency of the cement in the lower part of the model to fail to harden because of solution of the syrup by the water in the lower part of the model.) This asphalt has a somewhat lower viscosity than that of the syrup. In this case, the asphalt broke through to form a dome-like uplift, so that the compression zone is materially modified by intrusion of the fluid underlayer. Figure 14 was made with pure Baroid on asphalt. The deformation was made more rapidly by tilting the box at a steeper angle, which probably contributed to preventing a dome-like uplift, such as shown in Figure 13.

Table 1--Summary of measurements of properties of powder mixtures

Mixture (by volume)		Density (d)		Shear test				Angle of repose				Cliff height (H)		Calculated c from			
				Slope (tan ϕ)		Inter-cept		(ϕ)		(tan ϕ)				Intercept		Cliff height (c = dH/4)	
Shot	Baroid	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
pct	pct	g/cm^3				g		°	°			cm		g/cm^2		g/cm^2	
100	0	4.44	4.78	0.26	0.32	25	60	26	27	0.49	0.51	0.3	0	1.0	2.3	0.3	0
90	10	4.56	4.84	0.31	0.32	20	80	34	32	0.67	0.62	0.8	0	0.8	3.1	0.9	0
80	20	4.46	4.75	0.30	0.33	35	85	37	36	0.75	0.73	1.4	1.2	1.4	3.3	1.6	1.4
70	30	4.08	4.67	0.34	0.36	50	80	39	41	0.81	0.87	1.8	2.7	1.9	3.1	1.8	3.2
60	40	3.92	4.19	0.32	0.38	30	60	44	43	0.97	0.93	3.0	3.8	1.2	2.3	2.9	4.0
50	50	. . .	3.92	. . .	0.45	. .	60	. .	44	. . .	0.97	. .	4.6	. .	2.2	. .	4.5
					(0.33)		(55)		(44)		(0.97)						
40	60	3.28	3.42	0.39	0.33	50	45	48	43	1.11	0.93	5.5	6.1	1.9	1.6	4.5	5.2
					(0.28)		(35)		(42)		(0.90)						
30	70	. . .	3.20	. . .	0.30	. .	40	. .	44	. . .	0.97	. .	6.9	. .	1.6	. .	5.5
20	80	2.30	2.40	0.41	0.37	50	40	52	46	1.28	1.04	7.0	7.1	1.9	1.6	4.0	4.3
10	90	. . .	2.06	. . .	0.37	. .	55	. .	46	. . .	1.04	. .	6.9	. .	2.1	. .	3.6
0	100	. . .	1.80	0.74	0.70	25	20	45	48	1.00	1.11	6.0	8.7	1.0	0.8	. .	3.9
25[a]	75	. . .	1.33	. . .	0.72	. .	10	. .	44	. . .	0.97	. .	3.8	. .	0.4	. .	1.3

[a] Cement used in place of shot

A, Observations by Thomas Cowan B, Observations by Shirley Price

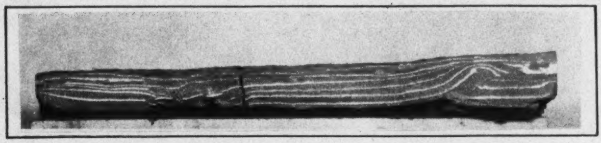

Fig. 7--Structure Section; 75 per cent steel shot, 25 per cent Baroid, syrup underlayer

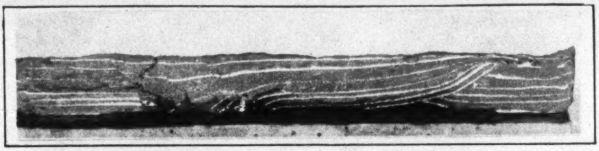

Fig. 8--Structure Section; 75 per cent steel shot, 25 per cent Baroid, syrup underlayer

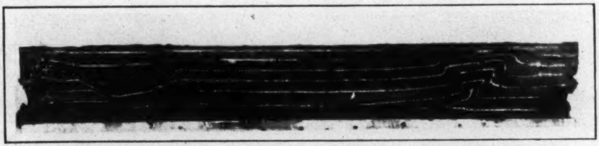

Fig. 9--Structure Section; 100 per cent steel shot, syrup underlayer

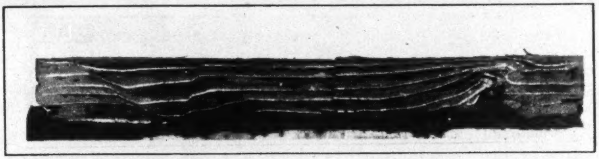

Fig. 10--Structure Section; 100 per cent steel shot, syrup underlayer

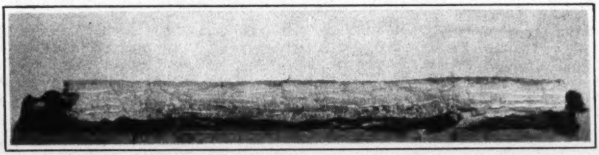

Fig. 11--Structure Section; 100 per cent Baroid, syrup underlayer

(The cement was used when it was found that Baroid by itself does not set as a cement when wet, while the Baroid-steel shot mixture sets quite hard, with appreciable evolution of heat, probable from oxidation of the iron. However, the Portland cement-Baroid mixture does not set well either, so that this mixture was little better than Baroid alone. The technique of "frosting" the powder "cakes," developed later (see Fig. 14), however, makes it quite simple to handle the poorly cementing mixtures.)

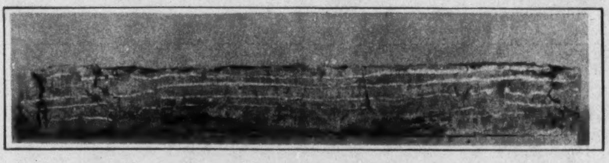

Fig. 12--Structure Section; 75 per cent Baroid, 25 per cent Portland cement, syrup underlayer

Fig. 13--Structure Section; 75 per cent Baroid, 25 per cent Portland cement, asphaltum oil layer

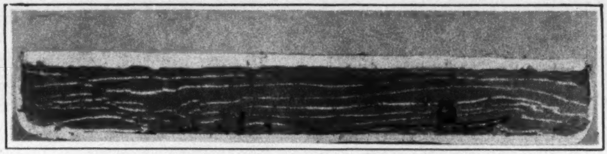

Fig. 14--Structure Section; 100 per cent Baroid, asphaltum oil underlayer

There is a marked difference in the character of the structures formed with the different mixtures but with other conditions the same. The models made with fine powder only (see Figs. 11 and 14) show much less definite overthrusting in the zone of compresssion, while the opening up and thickening in the zone of tension are comparable with that in the models made with mixtures containing more shot. This difference is probably caused by greater compressibility of the fine powder, so that the compression is taken up largely by compaction and increase in density rater than by overthrusting. This suggests that future measurements of model materials should include a compaction test, following some of the techniques developed in soil mechanics.

Mechanics of granular material--To understand the behavior of the powdered model materials and to estimate the model ratios, it is necessary to review briefly some of the principles of the mechanics of a body of loose granular material. There is a considerable body of literature on this subject in soil mechanics and civil engineering publications, including relatively recent books in English by TERZAGHI [1944] and KRYNINE [1941].

The commonly used relation for the shearing resistance of porous materials is the Coulomb equation

$$s = c + \sigma \tan \phi \quad \dots\dots\dots 1$$

where s is the shear strength along any plane through the point under consideration, c is the cohesion of the material, σ is the normal stress on the same plane and ϕ is the angle of internal friction. The quantities c and σ are usually assumed constant for a given material and we shall make the same assumption. The significance of this relation is shown in the Mohr diagram for this case (see Fig. 15). In this diagram, s and σ are plotted as vertical and horizontal coordinates, respectively, and the other quantities are related as shown. According to the Mohr theory of limiting stress, which is commonly used in soil mechanics and which we shall also assume to be applicable to powder model materials, the straight lines DE and DF are the boundaries between the sector of angle 2ϕ, which contains the pairs of values of s and σ for which the material is within the elastic limit, and the area outside this sector, which contains the pairs of values of s and σ for which flow or fracture occurs. It is interesting to note that this use of the Coulomb equation and the Mohr theory amounts to a generalization of the well known law of frictional resistance, for a body sliding on a plane, applied to the grains of the material.

If the Mohr diagram is applicable and the model material actually represents the sediments in nature, the sediments must possess a Mohr diagram of their own, which must be geometrically similar to that for the model material. A similar application of the Coulomb equation and Mohr diagram has already been used in the study of plastic materials [NADAI, 1928, pp. 492-494] and, if we assume that the sediments are plastic materials, we can then postulate the same setup as for the granular materials. However, it may be more natural to consider that, since even layered sediments are actually composed of blocks and chunks, the same is true in fact of such massive materials as granite, the model materials really represent the geologic ones, especially when considering dimensions of such size that statistical averages of large numbers of grains or chunks are involved. In that case, we then must have geometrically similar Mohr diagrams for the two.

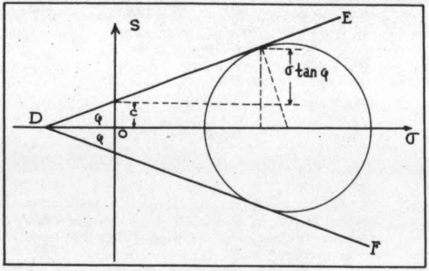

Fig. 15--The Mohr diagram

This means that the value of ϕ for the model material must equal the value of ϕ for the sediments and the model ratios, that is, the value in the model divided by the value in the prototype for c and σ must both equal that for s (stress or strength). Moreover, whether flowage or breaking occurs, seems primarily to be a matter of geometical configuration; thus a sharp fold may break instead of flowing. We shall assume that both in the case of the sediments and in the case of the model materials, the flowing and breaking strengths are the same. It would be unecessary to assume this if we could arrange to have the model ratios of the two types of strength the same or know from other considerations that they were the same. However, it is probably not essential from a practical standpoint that the two model ratios be closely the same, because it is likely that the cohesion term, c, in the Coulomb equation is negligible compared with the second term, except near the surface. If then, the values of ϕ are about the same for model and prototype, for rough approximations we may consider only the second term of the equation in computing the model ratios.

Physical properties of model materials--If we are to apply the foregoing considerations of the mechanics of granular materials to evaluate the scale ratios of model to prototype in nature, it is necessary that numerical values be found for the properties to be compared. Properties measured are as follows:

(1) Shear strength, s--(related to cohesion, c, and angle of internal friction, ϕ)-- This is a measure of the force required to shear a sample of the material and is measured by the simple apparatus of Figure 16. The sample is confined in a small square box, divided into two parts, the upper one being loaded with weights. A series of tests is made with loads from 0 to 1000 g, in 100 g steps, with the force required to shear the material being measured with the spring scale. The slope of the plot of shear force against load is tan ϕ; the intercept of this line on the vertical axis is a measure of c.

(2) Angle of repose, ϕ'--This is measured by simply pouring out the material into a conical pile and measuring the slope of the side of the pile. Measurements were made for piles of three to five different heights in ranges from one to three inches. In the older work on soil mechanics, the angle of repose, ϕ', was often considered as a good approximation to the angle of internal friction, ϕ. In general, it would be expected to be somewhat less for cohesionless materials

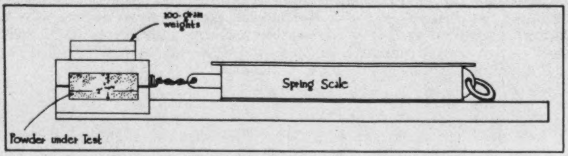

Fig. 16--Apparatus for shear test of powdered model materials

[KRYINE, 1941, pp. 165-166] but would be expected to depend on the height of the pile for cohesive materials [TERZAGHI, 1944, p. 8]. However, in the measurements which were made on the powders, there seemed to be no systematic variations with height and actually, from the measurements, tan ϕ' is about double tan ϕ.

(3) Cliff height, H (related to cohesion, c)--This is simply the height of an unsupported vertical cliff which the material will sustain. It is measured by piling up a sample of the material, smoothing off a horizontal top surface, then cutting down vertically into the middle of the pile and removing half to the depth of the cut, with successively deeper and deeper cuts, until the vertical "cliff" collapses (see Fig. 17). TERZAGHI [1944, pp. 152-155] gives the following relation between the cliff height, H, and the cohesion, c,

$$H = kc/d \ldots\ldots\ldots\ldots\ldots\ldots 2$$

where d is the density and k is a "constant" ranging from 2.67 to 5.14 with a common average value of around four for H in cm, c in g/cm^2, d in g/cm^3. The theoretical basis for this formula is very weak, and it is probably best considered as an empirical one. Recent work by SOKOLOVSKY [1942] has considered a related problem at length, that is, that, in the two-dimensional case, of finding for what loads on the upper horizontal surface, a given slope-curve will be possible. This theory might be applied to the "cliff height."

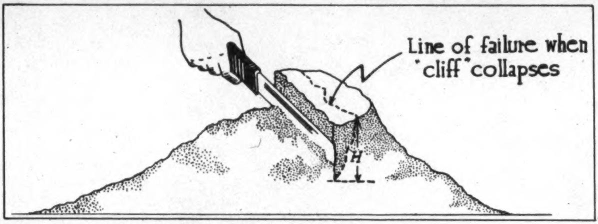
Line of failure when "cliff" collapses
H

Fig. 17--Measurement of "cliff height"

(4) Density d--The density is derived by the simple and direct process of weighing, with the spring balance of Figure 16, a small beaker filled to a mark representing a known volume. The only complication is that measurements are somewhat erratic due to variations in packing and consequent variations in porosity of the granular mass.

Results of measurements--As mentioned in the experimental section, the powdered material which seems most useful is a mixture of steel shot and Baroid. The steel shot is composed of nearly spherical grains, quite uniform in size, with an average diameter of 0.0190 inches, based on six measurements which ranged from 0.0185 inches to 0.0195 inches. The Baroid is the common oil well drilling mud weighting material and is principally finely ground (passes 300 mesh screen) barium sulphate, with grain density about 4.3 Measurements of the four properties, tan ϕ, ϕ', H, d, listed in the previous section were made for a series of shot-Baroid mixtures, from 100 per cent shot to 100 per cent Baroid, in 10 per cent steps (percentages by volume). The numerical values are summarized in Table 1. Plots of the individual shear test measurements are given by Figure 18. The ordinates, s', are spring forces in g; abscissae, σ', are applied loads in g. $s = s'/A$; $\sigma = \sigma'/A$, where A is the cross-sectional area of the plane of shear, A = 4 square inches in these test. A graphical summary of most of the measurements is given by Figure 19.

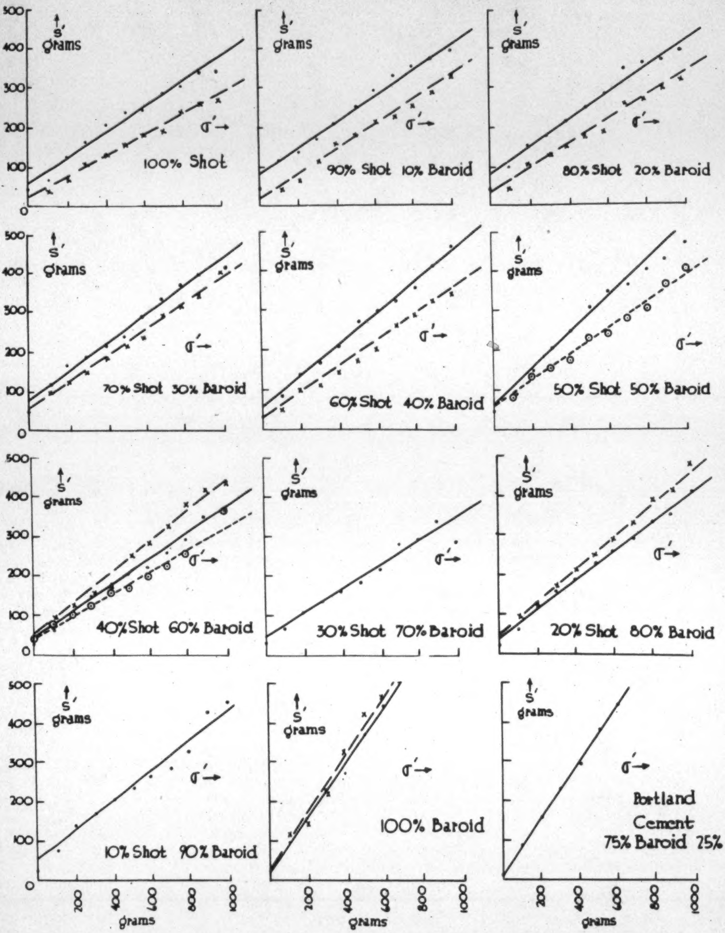

Fig. 18--Plots of individual shear-test measurements

In general, the measurements of properties of the powders cannot be considered very satisfactory. Part of the trouble may be caused by the rather crude nature of the tests, but a greater and, at present, much more important difficulty is the lack of a really adequate theory of such materials. The discrepancies between the two measurements of c, from cliff height and from shear test, and between ϕ and ϕ', from shear test and from angle of repose, are not likely to be explained by refinement of the kinds of tests made. Further progress will require more study of the fundamental mechanics of granular materials and methods of evaluating pertinent properties. However, at the present stage, the measurements are adequate to give approximate values of the required physical properties and to serve as a basis for estimating the order of magnitude of the model ratios.

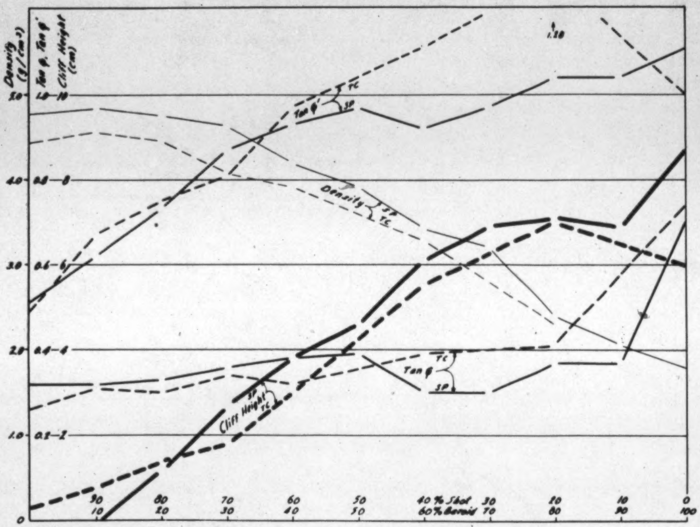

Fig. 19--Summary of measurements of angle of internal friction (φ), angle of repose (φ'), cliff height, and density, for various shot-Baroid mixtures (per cent by volume)

Physical constants of the sediments--In order to estimate the model ratios, we must have numerical values for certain physical properties of the sediments to compare with the values determined by the measurements on the model materials. We can make rough estimates of certain of the required numerical values for the properties of rocks in nature, as follows:

(1) Shear strength--The compressive strength, S, of the materials in the upper part of the Earth's crust is probably of the order of 10^9 dynes/cm^2, as inferred from measured crushing strength of such material as basalt, granite, and limestone [JEFFREYS, 1935, p. 94]. If we assume a two dimensional state of stress, the shearing stress, s, on a plane inclined at an angle α to the direction of compression will be $S \sin \alpha \cos \alpha$, for which the maximum value is for $\alpha = 45°$ and is $s = S/2$. However, experimentally, fracture usually occurs with α about 30° [JEFFREYS, 1935, p. 151], which yields a value of $s = 0.4$ S. We shall therefore use for s the value 4×10^8 dynes/cm^2, although, since sediments are probably somewhat weaker than the rocks mentioned above, actually all that is reasonable to conclude is that the value of s is of the order of 10^8 dynes/cm^2.

(2) Angle of internal friction--There seems to be no simple way of obtaining a representative value of ϕ for the sediments. An average value for medium and coarse dry sand is from 30° to 35° [KRYNINE, 1941, p. 172], which values may or may not be applicable. However, from such nebulous data as are available, it seems that a range in tan ϕ of more than a fraction of an order of magnitude is improbable, and about the best we can do now is to assume that ϕ in model and in prototype are the same.

(3) Cohesion--The analogy to the "cliff height" experiments would be the finding in nature of maximum heights of substantially vertical cliffs composed of various materials. This is difficult because of the modifications by erosion. However, some limits may be approximated. For instance, a granite cliff, El Capitan, at Yosemite Valley stands almost shear for a height of about 3000 feet (there may be higher examples at other places in the world which are unknown to the writers). With the formula for H, the calculated value for c from the height and density (assumed value 2.7) for this cliff is $c = 6.0 \times 10^7$ dynes/cm^2, which is a minimum for this case, since the cliff has not collapsed, but may be high as an example for sedimentary materials.

(4) Density--Values of density in nature vary over a comparatively narrow range. If we take the average value as 2.4 g/cm^3, nearly all sedimentary rocks are included in a range of ±20 per cent from this value. This is small compared to the possible variations in the other quantities considered, and the density ratio is the least uncertain model ratio.

Estimation of model ratios--HUBBERT [1937] has shown that for a proper scale model certain relations between the ratios of properties of model to prototype must be satisfied. The ratios in the sense (model-to-prototype, so that most ratios are small numbers) with which we are concerned are length λ, density δ, time τ, viscosity ψ, and strength or stress σ. Note that for uniformity we are following Hubbert's notation. Although we have previously used σ with a different meaning in the Coulomb equation, the context will serve to distinguish between the two uses.

Since the motions involved are very slow, inertial forces may be ignored, as in the treatment of salt-dome models by HUBBERT [1937]. The important ratios are therefore those of strength or stress, both with the same model ratio and viscosity. From the present viewpoint, the only reason the viscosity is involved is the fact that viscous flow of salt (of syrup in the model) occurs. If, however, it is safe to assume in these problems the conclusion of DOBRIN [1941] from experiments with two viscous fluids, that the viscosity or plasticity of the rock salt itself is a minor factor, then we can ignore the viscous properties of the model syrup and concern ourselves only with the overlying sedimentary material and its model representation by the granular material. The only evidence on this point presented here is that of Figures 11 to 14, which show models using different underlayers. This evidence is not clear cut.

The first set of fundamental ratios will be taken as those of length, density, and time, λ, δ, τ; then the ratio of strength or stress ($\sigma = \delta\lambda$), and the ratio of viscosity ($\psi = \delta\lambda\tau$) will be derived ratios. The second set of fundamental ratios will be taken as δ, τ, σ; then the model ratios for length ($\lambda = \sigma\delta^{-1}$) and for viscosity ($\psi = \sigma\tau$) will be derived ratios.

The following paragraphs contain estimates of the scale of the model from the available data and guesses.

(1) From shear strengths--For the sediments in nature, as we have seen in the preceding section, we may estimate density d = 2.4 g/cm^3, and shear strength s = 4 × 10^8 dynes/cm^2. For the powder material, the mixture used for the models shown in Figures 7 and 8 was about 3/4 shot and 1/4 Baroid. From Figure 19 the density d = 4.5 g/cm^3. From Figure 18 a reasonable value of s′ for zero load is 60 g, while from Figure 19 we estimate tan ϕ as 0.33. From these values we derive the Coulomb equation for this mixture,

$$s = 2300 + 0.33\sigma \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where s and σ are in dynes/cm^2. From this equation we estimate that s for a load of three inches of powder is 13,400 dynes/cm^2. Thus, the strength ratio $\sigma = 13{,}400/4 \times 10^8 = 0.34 \times 10^{-4}$, the density ratio $\delta = 4.5/2.4 = 1.9$, and therefore the length ratio $\lambda = \sigma\delta^{-1} = 0.18 \times 10^{-4}$, and the scale factor is $1/\lambda = 5.6 \times 10^4$.

Note that in this calculation we are using the second set of fundamental units, σ, δ, τ, and that the time factor drops out first, because the motions, even in the models, are so slow that inertial forces may be neglected and secondly, because we have assumed on the basis of the paper of DOBRIN [1941] that the viscous properties of the salt (or syrup) layer can be ignored for this work.

(2) From cliff heights--For the Yosemite cliff already mentioned, the height 3000 ft = 0.91 × 10^5 cm. For the 75 per cent shot and 25 per cent Baroid mixture, the cliff height from Figure 19 is 1.8 cm; therefore the length ratio $\lambda = 1.8/1.07 \times 10^5 = 0.20 \times 10^{-4}$ and the scale factor is $1/\lambda = 5.0 \times 10^4$. Since the density ratio $\delta = 4.5/2.7 = 1.7$, the strength ratio $\sigma = \delta\lambda = 3.4 \times 10^{-5}$. If we compute s for the model material for a load of 1.8 cm, we find s = 4900 dynes/cm^2. The corresponding prototype value of s is then 1.4 × 10^8 dynes/cm^2 or greater, since the cliff is still standing. This value seems highly reasonable and helps to justify this method of deriving the length ratio. Note that we are here using the first set of fundamental units.

(3) From similarity to geologic structure--As is shown by Figure 20 (a and b), one of the model structures (see Fig. 8) is strikingly like the Turner Valley structure. For the structure shown, the approximate depth = 12,000 feet, and for the model the approximate depth is three inches, so therefore, the length ratio = 3/144,000 = 0.21×10^{-4} and the scale factor $1/\lambda = 4.8 \times 10^4$. If we use the density 2.7 g/cm^3 for the structure, the density ratio $\delta = 1.7$ and the strength ratio $\sigma = \delta\lambda$

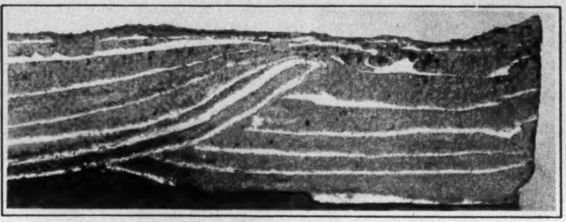

Fig. 20a--Enlargement of compression zone from Figure 8, showing similarity to geologic section below

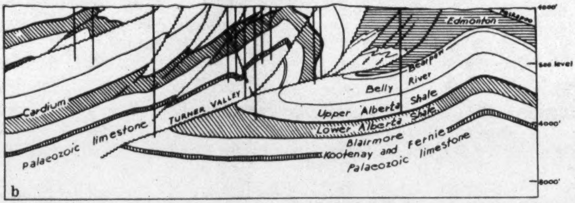

Fig. 20b--Cross section of Turner Valley, Alberta, Canada after G. S. Hume modified from later drilling (vertical and horizontal scales equal)

$= 3.6 \times 10^{-5}$. Since s in the model for a three-inch load is 13,400 dynes/cm^2, s for the prototype is 3.7×10^8 dynes/cm^2, again a reasonable value.

From the above considerations, it seems probable that the scale factor for the powder material models is about 5×10^4. On this basis, the present box is probably too small to simulate the Gulf Coast section, where we would expect the depth of about three inches in the box to represent the order of 20,000 feet of sediments, from which the required scale factor is about 8×10^4 which is probably larger than that actually achieved. It seems probable that more successful experiments would be made with a box having a depth of a foot and perhaps minimum horizontal dimensions of the order of five feet. This would require 25 cubic feet of material which, with density of about four would weigh over three tons.

Conclusions--The present study shows the practicability and value of the use of granular model materials for the study of geologic deformations and also indicates that the concept of a Mohr diagram for sediments and other geologic materials geometrically similar to that for the powder mixtures may be of importance in the explanation of such deformations.

The original purpose of obtaining models which would simulate grabens over salt domes was not achieved but the indications are that it might be with a much larger model. It seems probable that a combination of circumstances favorable to initiating a dome in a region of tension in the overlying material probably would result in grabens associated with domes; the region of tension appears to be an essential condition. This could be checked by building a box somewhat longer than it is wide with the bottom sloping on a curve to give an increasing slope, so that a zone of tension in the overlying material would be set up over a considerable width. It might also be done by providing a moveable bottom (rubber, or moveable sheets), but this seems less similar to possible conditions in nature. It would be especially important if a larger model box were built to try to make tests with ordinary sand, magnetite sand, or other materials which might be as satisfactory as the steel shot but much less expensive.

Various intriguing possibilities are evident for studying the relation between physical properties of geologic materials and the nature of the resulting geologic deformation by the use of the powder mixtures described or of others with "made-to-order" properties. For example, models could be made with the various layers composed of mixtures with properties corresponding to relatively competent and incompetent beds. Again, a possible variation is that of vibrating the box. This would, in effect, reduce the strength of the powder and perhaps is a factor with a counterpart in nature, since seismic activity undoubtedly contributes its effects to the mechanical properties of the materials involved in earth deformation.

Acknowledgments--The authors wish to acknowledge the assistance received in the experimental work from Thomas Cowan and Shirley Price (now Mrs. Shirley Cook). The drawings were prepared by Robert D. Craighead, Jr. and J. B. Brooks. The authors also wish to express their thanks to E. A. Eckhardt for permission to publish this paper.

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Transactions, American Geophysical Union Volume 28, Number 3 June 1947

REPORT OF THE COMMITTEE ON PHYSICS OF SOIL MOISTURE, 1946

F. J. Veihmeyer, Chairman

For many years, hydrologists have been attempting to determine a suitable base from which soil-moisture contents may be reckoned. In the report of the Committee on Physics of Soil Moisture for the year 1937 [see "References" at end of report, VEIHMEYER, 1934], some of the so-called soil-moisture constants in use were discussed in detail by various investigators in the field of soil moisture.

Experience has shown that probably the best soil-moisture constant from which to calculate moisture conditions is the permanent wilting percentage. This term was suggested by VEIHMEYER and HENDRICKSON [1934] as a substitute for the term "wilting coefficient" by Briggs and Shantz. The latter defined the term in such a way that it implied a constant relation between the residual moisture content in the soil at the time plants permanently wilted, and the moisture equivalent. Since it has been shown that the ratio of these two values is not constant, the term "coefficient" leads to false implications. The term "permanent wilting percentage" means the actual moisture content in the soil at the time plants permanently wilt, that is, they will not recover when placed in a moist chamber or until water is added to the soil.

Some of the difficulties in obtaining an agreement between field and laboratory trials of the permanent wilting percentage have been discussed in a paper by HENDRICKSON and VEIHMEYER [1945]. The appearance of the indicator plants (sunflowers) which can be used to determine the permanent wilting percentage is illustrated in this paper so that a definite condition of wilting can be selected to correspond with permanent wilting. It is pointed out that the permanent wilting percentage is not a unique value, but is a small range of soil-moisture conditions within which permanent wilting takes place. The limits within which the value may be determined are given. The fact that in small containers there is a continued extraction of moisture from the soil after the plants permanently wilt has suggested the use of the terms "wilting range" and "ultimate wilting percentage" [TAYLOR, BLANEY, and McLAUGHLIN, 1934; TAYLOR and FURR, 1937]. The ultimate wilting percentage is defined as the moisture content of the soil at the time all of the leaves of the indicator plant are wilted. Since there is a considerable amount of water taken from the soil in small containers by the plants after they have permanently wilted, it is suggested that the permanent wilting percentage of soil in the field does not represent the lower limit of available water. The data presented in the paper by Hendrickson and Veihmeyer show that soil-moisture extraction curves plotted from results with plants under field conditions, slope downward approximately uniformly until they reach a moisture content at which there is a marked reduction in rate of extraction. This change in direction of the curve occurs slightly above the permanent wilting percentage obtained from sunflower plants in containers. After reaching this moisture content the curves, according to results in the field, continue nearly horizontal, showing that the soil moisture is slowly reduced to a minimum which is slightly below the permanent wilting percentage. This reduction is small, often not more than one per cent, even after three or four months.

The Committee is seeking data concerning the extraction of soil moisture after the plants growing in the field permanently wilt, and the Chairman welcomes comments.

The depletion of soil moisture below permanent wilting must be determined by empirical trials with different types of vegetation. A paper by Veihmeyer and Hendrickson showing the results obtained by field sampling will be sent to investigators in the field of soil moisture and similar data will be solicited from them. The paper and comments will constitute the report of the Committee. It is hoped that enough field data can be obtained to find out why the permanent wilting percentage, determined with indicator plants in small containers, sometimes shows small departures from the minimum soil-moisture contents found in the field. It is obvious that a suitable base from which to calculate the water which can be stored in soils is needed by hydrologists where the amount of water required to replenish or prime watersheds must be known in estimating probable runoff.

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REPORT OF THE COMMITTEE ON PRECIPITATION, 1946

Merrill Bernard, Chairman

Carlos Cabral
A. R. Codd
Leonard B. Corwin
Glen N. Cox
Robert W. Gay
W. G. Hoyt
J. W. Howe
Charles T. Hursh
J. Otis Laws
Luna Leopold
F. T. Mavis
A. K. Showalter
C. W. Thornthwaite
Waldo E. Smith

H. L. COLLINS (summary statement of the current status of the precipitation networks operated by the United States Weather Bureau and cooperating agencies)--The hydroclimatic network is now comprised of 3054 stations, operated under Weather Bureau management, of which 2356 are equipped with recording rain gages. The network of recording gages is financed from flood-control funds transferred to the Weather Bureau by the Corps of Engineers of the United States Army. In addition, records are obtained from approximately 400 recording and 915 non-recording rain gages maintained by agencies cooperating with the Weather Bureau in the collection of precipitation data. Records are available in the monthly Hydrologic Bulletins from 4369 stations (2789 recording gages and 1580 non-recording gages), making a total of 12,569 records available in Weather Bureau publications.

Since 1937 existing Weather Bureau networks of river and rainfall stations have been expanded in cooperation with the War Department to make available to the Corps of Engineers, through the River Forecasting Offices of the Weather Bureau, more frequent reports of river stages and rainfall. Reports are currently available from approximately 1500 stations in the principal river basins of the United States. Of these stations approximately 500 are operated in cooperation with the Corps of Engineers in the following reporting networks:

Lower Mississippi River
Upper Mississippi River
Ohio River
Willamette River
Los Angeles, Calif.
Merrimack River
Mobile, Ala.
Connecticut River
Yazoo River
Red River
Wallace Lake Reservoir (in La.)
Middle Arkansas River
Puyallup River
St. Francis River
Lower Arkansas River
Snake River
Delaware River
Illinois River

LUNA B. LEOPOLD (accomplishments of the Subcommittee on Hydrologic Data, Federal Inter-Agency River Basin Committee)--Under the Federal Inter-Agency River Basin Committee there has been set up a Subcommittee on Hydrologic Data to coordinate the hydrologic activities of various Federal agencies. The Subcommittee is in the process of developing an over-all plan for the expansion of the basic hydrologic network. Under the direction of the Weather Bureau, a series of maps has been prepared on which are shown the location of all hydrologic stations, concerning which the Weather Bureau had information. Copies of these maps have been distributed to field offices of all interested agencies with the request that the location of all precipitation stream-flow stations operated by, or known to the respective offices, be indicated on the maps. With these notations and corrections, the maps will be returned to the Subcommittee for final compilations.

At a later stage, regional meetings will be held to determine the locations and types of new installations to serve more completely the needs of all users of hydrologic data. The Subcommittee is concerned with many other topics. It has discussed and made recommendations concerning the allotment of radio frequency bands for the exclusive transmission of hydrologic data. It is also concerned with the coordination of the snow research which has been pursued by the Corps of Engineers and Weather Bureau at the Central Sierra and Upper Columbia Laboratories. The Subcommittee took up the matter of snow research coordination when the Bureau of Reclamation and the Forest Service indicated their desire to become cooperators in the program. As a result of the discussions held at the request of the Subcommittee, the various agencies were asked to consider a plan for the expansion of the existing Range and Forest Experiment Station at Fraser, Colorado, into a cooperative snow research laboratory as well as a forest-management experimental forest.

The Subcommittee is making arrangements by which the snow research data will be made available to all the cooperating agencies as soon as the data have been processed at a Central Analysis Unit. At a later date, the analyzed data will be published in some appropriate manner for the information of all hydrologists.

J. W. HOWE--Locally (near Iowa City, Iowa) we have been able to keep our Ralston and Rapid Creek records intact and are beginning a research project on the time of concentration on these areas which will, of course, involve some study of precipitation.

ROBERT W. GAY--The United States Weather Bureau, National Park Service, and the Tennessee Valley Authority, cooperatively, are conducting an investigation of snowfall and related weather data in the Great Smoky Mountains. The purpose of this investigation is to obtain scientific data on the phenomena of snowfall in this region, its depth, equivalent volume of water, and rates of melting.

During December, 1945 a series of seven special snowfall stations was established across the Great Smoky Mountains along the state highway between Gatlinburg, Tennessee, and Cherokee, North Carolina. Elevations at these stations range from approximately 1460 feet above sea level at the station near Gatlinburg to 5000 feet at the station at Newfound Gap, and down to 2100 feet at the Oconaluftee Ranger Station. During January, 1946 an additional station was established at the Forney Ridge parking area near Clingman's Dome. Records of snowfall, other precipitation, snow on ground, and water equivalent of snow on ground are obtained at all eight stations.

ASHTON R. CODD--In the Western States the trend of forecasting seasonal stream flow from precipitation data has grown rapidly during the past two or three years. This movement has been amplified by methods developed by the Weather Bureau, the San Francisco Public Utilities Commission, the Pacific Gas and Electric Company, and others. Although the idea is not new, this revival has been brought about by the use of advanced statistical methods to give a more complete answer to their forecasts than was being advanced by other index relations. This fact was very evident at the South Pacific Regional Meeting of the Section of Hydrology in February, 1946, held in Sacramento, California, where several related papers were presented and lively discussion followed.

The extensive analysis of precipitation data by these individual groups of hydrologists has resulted in an almost unanimous conclusion: There is great need for additional precipitation data at higher elevations. In most all cases the lack of data is in the zone of greatest water producing possibilities. This zone is invariably in the most isolated and uninhabited areas of the mountains.

The seasonal storage precipitation gage developed by the Weather Bureau has been found best suited to the collection of data from these areas. Eight stations equipped with these instruments during the fall of 1945 have demonstrated their efficiency and usefulness at remote locations throughout the Sierra. Private and public groups have combined to assist financially in a mutual expansion of the network of stations in isolated areas. Approximately 60 gages have been subscribed for installation this coming season.

MERRILL BERNARD--During the year an analysis unit similar to that organized in 1940 to make hydrometeorological studies for the Engineer Department, Corps of Engineers, was set up within the Weather Bureau to serve the Bureau of Reclamation. These cooperative studies are closely coordinated with the Denver offices of the Bureau of Reclamation and with the cooperative studies of the Engineer Corps.

The Weather Bureau's thunderstorm project completed a successful season in Florida. The characteristics of thunderstorms were intensively studied, practical use being made of a dense network of ground stations, radar and airplane flights into strom areas. The project will be moved to central Ohio for the thunderstorm season in the spring and summer of 1947.

U. S. Weather Bureau,
Washington 25, D. C.

(Manuscript received December 10, 1946, presented at the Twenty-Seventh Annual Meeting, Washington, D. C., May 29, 1946; open for formal discussion until November 1, 1947.)

South Duxbury, Plymouth County,
Massachusetts, U.S.A.,
January 31, 1947

INTERIM REPORT 1

Committee on the Social Value of the Earth Sciences (CSVES), International Union of Geodesy and Geophysics (IUGG)[a]

Following discussion on name, functions, and financing of this Committee by the Extraordinary Assembly, held at Cambridge, England, last summer.

Resolution 13: (a) To adopt Resolution 17, passed by the Extraordinary Meeting of the Executive Committee held at Oxford, England, November, 1945, namely: "A Committee on the Social Value of the Earth Sciences be formed, under the chairmanship of Dr. R. M. Field, with the object of preparing a general statement on the value of the Earth Sciences for human welfare, and of instituting such forms of publicity as may from time to time be desirable."

(b) That a Committee with the title "Committee on the Social Value of the Earth Sciences" be formed.

(c) That the Committee be comprised as listed in the Oxford Report with the addition of the name of Professor Solberg (Norway) and with power to co-opt other members.

(d) That the Committee should, for the present, be an independent Committee under the Union.

(e) That no serious demands should be made by the new Committee on the funds of the Union.

(f) That the Committee be asked to prepare a draft pamphlet outlining the scope and services of the Union for the information of countries whose adherence the Union desires. The final form of the pamphlet will be decided by the Bureau.

Group of members and guests of CSVES at entrance of Suburban Laboratory for Cosmic-Terrestrial Research, Needham, Massachusetts, September 10, 1946
[Left to right: Thom, Almy, and Seymour (front row); Fleming, Mrs. Oliver, Philbrick, Miss Crouch, Mrs. Chirurg, Hunt, Field, Stetson (back row)]

Group of members and guests of CSVES at William F. Clapp Laboratories, Duxbury, Massachusetts, September 9, 1946
[Left to right: Tracy, Hunt, Fleming, Brewster, Seymour, Clapp, Thom (photographer, Anderegg)]

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[a] Presented to meeting on October 25, 1946, of the Executive Committee of the AGU by J. A. Fleming.

The full membership of the Committee is now constituted as follows: R. M. Field (USA), Chairman; C. F. Baeschlin (Switzerland); G. Cassinis (Italy); Sydney Chapman (Great Britain); Jean Coulomb (France); B. Helland-Hansen (Norway); G. Lenox-Conyngham (Great Britain); N. E. Nörlund (Denmark); Noel J. Ogilvie (Canada); Hans Pettersson (Sweden); Jean Rothé (France); P. C. Sanchez (Mexico); H. Solberg (Norway); W. T. Thom, Jr. (USA); T. G. Thompson (USA); F. A. Vening Meinesz (Holland).

In September, 1946, Chairman Field of the Commission on Continental and Oceanic Structure (CCOS), IUGG, called a meeting of CCOS at Ottawa, Canada. Attending were: Chairman Field; the Secretary (J. A. Fleming); H. H. Hess (member and Chairman, Committee on Geophysical and Geological Study of Ocean Basins, AGU); F. A. Vening Meinesz (member); W. A. Heiskanen (member); and N. J. Ogilvie (member). Also attending were W. T. Thom, Jr. (member, CSVES, and Chairman, Committee on Geophysical and Geological Study of Continents, AGU); the Director, Canadian Geological Survey; the Director, Canadian Arctic Institute; several other Canadian experts, including R. M. Stewart, Dominion Astronomer; the Chairman (H. T. Stetson), Committee on Cosmic-Terrestrial Relationships, AGU, and Fred Anderegg, Chairman, Committee Aerial Photography, IUGG.

Immediately following the Ottawa Meeting of CCOS, the Chairman called a meeting of CSVES at Duxbury, Massachusetts. Attending were: Chairman Field and Secretary Fleming of CCOS, the latter of whom reported on the Ottawa Meeting; W. T. Thom, Jr. (member); H. T. Stetson; Fred Anderegg (Chairman, Committee on Aerial Photography of CCOS); and several other experts on the Earth sciences, business, publicity, and theology. Meinesz (member) and Chapman (member) expected to attend but were unable to do so. Meetings of CSVES were also held at the William F. Clapp Laboratories, Duxbury, and at the Suburban Laboratory for Cosmic-Terrestrial Research (H. T. Stetson, Director) of the Massachusetts Institute of Technology.

For a summary of both the Ottawa and Duxbury meetings, see Report by J. A. Fleming, June 1947 number of the Transactions [pp. 473-477]. Separates will be mailed to all members of CCOS and CSVES immediately following publication.

In the meantime, please note under Resolution 13: (c) What services of others should this Committee co-opt? (Will each member immediately make his nominations to the Chairman?) (f) Immediately notify the Chairman what you think are the principal reasons why those countries whose adherence IUGG desires should do so.

Important: There will be a New England Meeting of the AGU, September 17 to 23, 1947. Will you be able to attend that meeting? If not, do you expect to be in the United States before next September?

Richard M. Field, Chairman,
CCOS and CSVES, IUGG

INTERIM REPORT 2

Committee on Publicity

Re Cambridge Resolution 13: ". . . . . instituting such forms of publicity as may from time to time be desirable." At the request of the Chairman of the Committee, the following gentlemen have accepted: E. W. Brewster, President, Plymouth Cordage Company; E. M. Crane, President, D. Van Nostrand Company; J. A. Fleming, President, International Council of Scientific Unions; E. L. D. Seymour, Horticultural Editor, American Home Magazine; H. T. Stetson, Director, Cosmic-Terrestrial Laboratory, Massachusetts Institute of Technology; Frans Verdoorn, Editor, Biologia; H. Z. Walck, Vice-President, Oxford University Press; and W. L. Valentine (recently deceased), Editor, Science. Suggested: J. Needham, S. Chapman, and J. M. Stagg.

At the request of the Chairman, the following gentlemen have accepted appointment as Advisers on Theology and Metaphysics: Sir Richard Tute, Author of "After materialism--What?" and "New Wisdom" (in publication); Rev. W. R. Hunt, Unitarian. Suggested: James B. Macelwane, S. J., Seismologist.

Please suggest immediately to the Chairman of CSVES, IUGG, other nominations.

It is important to note there will be a combined meeting of CCOS and CSVES of IUGG, September 23 to 25, 1947, at South Duxbury, Plymouth County, Massachusetts, U.S.A.

Transactions, American Geophysical Union Volume 28, Number 3 June 1947

MEETINGS OF INTERNATIONAL COMMISSION ON CONTINENTAL AND OCEANIC STRUCTURE (CCOS) OF THE INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS (IUGG), OTTAWA, CANADA, SEPTEMBER 2 TO 4, 1946[a]

Morning, September 2, 1946

The Commission with guests assembled in one of the conference rooms of the Chateau Laurier at 09^h 35^m.

Present: R. M. Field of United States (Chairman, CCOS);W. A. Heiskanen of Finland; Noel J. Ogilvie of Canada; J. T. Wilson of Canada; and F. Anderegg, J. A. Fleming, H. H. Hess, H. T. Stetson, and W. T. Thom, Jr., of United States.

The letter dated July 29, 1946, signed by the Secretary upon instruction of the Chairman, calling the meeting and extending invitation to members and guests, was read.

According to its original instructions at the Edinburgh Assembly, the Commission co-opted the essential services of those who are not among its members. The official status of those present at the meeting were as follows: Dr. Harry H. Hess, Chairman, Committee on Geophysical and Geological Study of Oceanic Basins, American Geophysical Union (AGU); Dr. W. T. Thom, Jr., Chairman, Committee on Geophysical and Geological Study of Continents, AGU; Dr. Harlan T. Stetson, Chairman, Committee on Cosmic-Terrestrial Relationships, AGU; Dr. J. A. Fleming, General Secretary, AGU; Colonel Jack Wilson, Canadian Arctic Institute; Dr. F. A. Vening Meinesz of Holland; and F. Anderegg, Aerial Photographer to CCOS. Dr. Sydney Chapman, Queen's College, Oxford, England, and Dr. B. Helland-Hansen, President, IUGG, were also invited but unfortunately could not attend because of failure of transportation facilities and illness, respectively. It is to be noted that B. Helland-Hansen, S. Chapman, N. J. Ogilvie, W. T. Thom, Jr., and R. M. Field are members of the new Committee on the Social Value of the Earth Sciences (CSVES), IUGG.

The tentative agenda for the meeting, as prepared by Chairman Field, and for the meetings in Massachusetts, to follow later, of CSVES, were as follows:

Tentative agenda for the Ottawa Meeting of CCOS, September 2 to 4, 1946

Subject A: Geodesy and its interrelations with all other phases of the Earth's sciences (geonomy)

Panel: (a) N. J. Ogilvie, Chairman, Canadian Committee, IUGG
(b) W. A. Heiskanen, Director, Isostatic Institute, Helsinki
(c) F. A. Vening Meinesz, Director, Geophysical Institute, Amersfoort; President, International Association of Geodesy

Subject B: Tectonophysics and its interrelations with all other phases of the Earth's sciences (geonomy)

Panel: (a) R. M. Field, Chairman, Commission on Continental and Oceanic Structure, IUGG
(b) W. T. Thom, Jr., Chairman, Committee on Geophysical and Geological Study of Continents, AGU
(c) H. H. Hess, Chairman, Committee on Geophysical and Geological Study of Oceanic Basins, AGU

Subject C: Cosmic Terrestrial Relations (Cosmocology)--interrelations with all other phases of the Earth's sciences (geonomy)

Panel: (a) H. T. Stetson, Chairman, Committee on Cosmic-Terrestrial Relationships, AGU
(b) Sydney Chapman, President, Association of Meteorology, IUGG
(c) J. A. Fleming, President, Association of Terrestrial Magnetism and Electricity

Tentative agenda for meetings in Duxbury and Needham,
Massachusetts, of CSVES, September 9-11, 1946

Subject A: Report on results of Ottawa meeting

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[a] A summary of the work of the Commission was presented by J. A. Fleming on October 25, 1946, at the meeting of the Executive Committee of the AGU.

Panel: (a) J. A. Fleming, President, International Council of Scientific Unions
(b) R. M. Field, Chairman, Commission on Continental and Oceanic Structure, IUGG
(c) H. H. Hess, Chairman, Committee on Geophysical and Geological Study of Oceanic Basins, AGU

Subject B: Conference to determine those phases of Geophysics, and their interrelations with other named departments of science, which are of benefit to all men and inimical to none

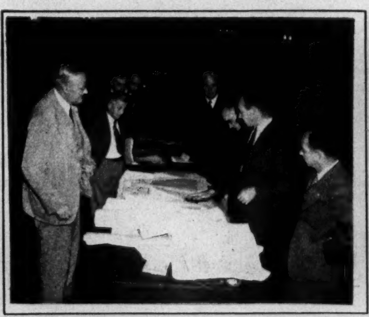
Panel: (a) Sydney Chapman, Queen's College, Cambridge, England
(b) Frans Verdoorn, Editor, Chronica Botanica
(c) E. L. D. Seymour, Vice-President, American Horticultural Council

Subject C: Committee on the Social Value of the Earth Sciences--Its policy, procedure, and interrelations (if any) with other named organizations, private or governmental

Panel: (a) J. Douglas Brown, Industrial Relations
(b) J. A. Fleming, President, International Council of Scientific Unions
(c) H. H. Beverage, Vice-President, Radio Corporation of America (alternates: Haradan Pratt, Gano Dunn)
(d) E. W. Brewster, President, Plymouth Cordage Company
(e) D. H. McLaughlin, President, Cerro de Pasco Corporation
(f) Julian Boyd, Librarian, Princeton University
(g) R. C. Stanley, President, International Nickel Company
(h) J. O. LaGorce, Vice-President, National Geographic Society
(i) W. T. Thom, Jr., former member Executive Committee, Summer School of Geology and Natural Resources, Princeton University
(j) Rev. W. R. Hunt of Duxbury
(k) Rev. J. H. Philbrick of Duxbury

The Chairman announced that the Eighth General Assembly of the IUGG has now been definitely set by the Extraordinary General Assembly of July 29 to August 2, 1946, at Cambridge, for September, 1948 in Norway upon invitation of the Norwegian Government. He also reported that B. Gutenberg of United States and B. Helland-Hansen of Norway had sent regrets they could not be in attendance. He also referred to the last-minute difficulty in obtaining air transportation that prevented the attendance of Sydney Chapman.

Because Vening Meinesz could not reach Ottawa before the afternoon of September 2 on his return as delegate of IUGG at the Caracas meeting of the Pan American Institute of Geography and History, the scheduled discussion for the first session of geodesy and its interrelations with all other phases of the Earth's sciences was replaced by that on tectonophysics.



Meeting of CCOS, Chateau Laurier, Ottawa, Canada, September 2, 1946
(Left to right: Vening Meinesz, Heiskanen, Thom, Stetson, Ogilvie, Fleming, Wilson, Hess)

Heiskanen and Vening Meinesz at Ottawa, Canada, September 2, 1946

Heiskanen spoke briefly on geophysical progress during the war in Finland and expressed his thanks for the opportunity of taking part in the meetings.

Thom then introduced the discussion on tectonophysics with particular reference to the dynamics and mechanics of the globe, sources of the Earth's interior energy and the extra-terrestrial influences involved and effects on the Earth's crust. Stetson, Thom, Hess, Heiskanen, and Wilson discussed the subject at length. Wilson presented a fine series of charts of Canada on geological and geophysical interrelations.

The morning session adjourned at $12^h 30^m$.

Afternoon, September 2, 1946

The afternoon session was called to order at $14^h 15^m$ with Ogilvie presiding. This session was attended by all those present in the morning and by F. A. Vening Meinesz of Holland (arrived early in the afternoon) and R. Meldrum Stewart of the Canadian Dominion Observatory and R. Shaw of the Canadian Geological Survey.

After introductory remarks Ogilvie called on Heiskanen, Meinesz, Hess, Field, Fleming, and Stewart, each of whom discussed at length various features and interrelations of the Earth's sciences with particular relation to the Commission's activities and geodesy.

Field announced the subjects for the meetings of September 3 and 4. Wilson extended an invitation for all present to dinner at the Rideau Club.

The meeting adjourned at $16^h 20^m$.

Morning, September 3, 1946

The Commission, with guests, assembled in the conference room at the Chateau Laurier at $09^h 30^m$.

Present: R. M. Field (Chairman of Commission); F. Anderegg; J. A. Fleming; W. A. Heiskanen; H. H. Hess; F. A. Vening Meinesz; Noel J. Ogilvie; H. T. Stetson; R. Meldrum Stewart; W. T. Thom, Jr.; and Squadron Leader J. C. Scott, and J. H. Meek of the Research for Defense Division of the Canadian Radio Wave Propagation Committee. J. T. Wilson could not be present since he went to Toronto to take up his new duties as Professor of Geophysics there.

Field made announcement of the meeting of the CSVES of IUGG called for September 9-10 at South Duxbury, and September 11, 1946, at Needham, Massachusetts.

Stetson opened the discussion on cosmic-terrestrial relations (cosmocology) and interrelations with all other phases of the Earth's sciences. He referred in particular to interrelations and outstanding questions involved in the ionospheric and radio-wave propagation fields of investigation. He quoted largely from a report made to the President of AGU. Extended discussion followed by Fleming, Scott, Meinesz, Field, Thom, and Stewart.

Because of the importance in geodesy and geophysics of settling the question of the velocity and variability in the effective velocity of radio waves, along lines first proposed by use of an airplane by Stetson to AGU, it was suggested that the Commission should urge that the proposed experiment be undertaken, that every cooperation be given to obtain the requisite facilities to accomplish the experiment, and that the Secretary of the Commission be authorized to communicate with appropriate agencies to expedite action. This subject, following the suggestion of Ogilvie, was further discussed in detail at a luncheon meeting by Scott, Meek, Stetson, and Fleming. It was suggested that the Canadian Radio Wave Propagation Committee be invited to consider whether that Committee might not find facilities and personnel available. (Address: Chairman, Canadian Radio Wave Propagation Committee, Research for Defense Division, Room 3301, Naval Service Headquarters, Ottawa, Canada; Wing Commander G. M. Fawsett, RCAF, is Chairman of that Committee.)

The morning session adjourned at $11^h 45^m$.

Afternoon, September 3, 1946

The meeting was resumed at 14^h 20^m. Those present were as for the morning session with the exception of Scott and Meek.

Following report by Fleming and Stetson the Secretary was unanimously authorized to send, on behalf of the Commission, statement and recommendation looking to the provision of facilities and the accomplishment of the research on the effective velocity of radio waves.

Stetson then continued his report on cosmic-terrestrial relationships of geophysics. He gave emphasis to the need of requirements for location of ionospheric stations in the postwar program and network, especially as all of the many stations so profitably established during the war for defense needs in radio communication could not be expected to continue.

Fleming was then called upon to discuss various aspects of geomagnetism and its cosmic interrelations with particular emphasis on ionospheric phenomena and results of isoporic analyses, study of magnetic anomalies, and development of instrumental equipment for aerial magnetic surveys.

Heiskanen, who had to address a meeting of his compatriots in Montreal, was excused with thanks at 15^h 25^m.

Stetson told of the application of coronagraphic observations (particularly at Climax, Colorado) to forecasts of disturbances in the ionosphere and thereby to prediction for selection of proper frequencies of radio communication.

Hess told of research during the war on ocean bottom and transmission of waves, caused by explosions, through the Earth's crust and indicated their great potential value in investigations of interest to the Commission.

Thom and Meinesz commented on the need of, and careful selection of, stations to obtain automatic records (tiltmeters, gravimeters, horizontal pendulums) for study of behavior of the Earth's crust.

Stewart and Field remarked on the valuable data resulting from research over the great Canadian region bearing on geology and geophysics both theoretically and economically. Thom emphasized the large contribution Canadian colleagues have made in this regard.

The afternoon session adjourned at 16^h 00^m.

Morning, September 4, 1946

The Commission and guests assembled for the final session of the Ottawa meeting at 09^h 45^m.

Present: F. Anderegg; R. M. Field; J. A. Fleming; H. H. Hess; F. A. Vening Meinesz; Noel J. Ogilvie; H. T. Stetson; W. T. Thom, Jr.

Chairman Field called attention to an announcement received from E. C. Bullard of a luncheon in Cambridge, England, on October 5, to celebrate Sir Gerald and Lady Lenox-Conyngham's 80th birthdays (both this year). The meeting agreed unanimously to cable a message of congratulation as follows:

Ottawa, September 4, 1946

Lady and Sir Gerald Lenox-Conyngham
Grange Road 79, Cambridge, England

Ogilvie, Stewart, J. T. Wilson, Shaw, Meinesz, Heiskanen, Fleming, Field, Stetson, Thom, Hess, Anderegg send hearty congratulations and felicitations your one hundred sixty years.

International Commission on Continental and Oceanic Structure, IUGG

Vening Meinesz stated that he would not be able, much to his regret, to attend the CSVES meetings in Massachusetts because of his obligations to take up questions, Toronto and Montreal, on international exchange of scholars between Canada and Holland for which his departure by steamship for home on September 25, 1946, allowed so little time. Ogilvie also stated it would be impossible for him to attend because of accumulated matters during his long absence in Alaska, from where he has just returned. They were therefore excused with regret.

Field described the responsibilities of CSVES as laid down by IUGG and as visualized by him. On Thom's suggestion it was agreed that each one present should mail Field carefully thought-out comments or counter suggestions and that the Chairman then exercise unifying influence and send preliminary report by mail to members of CSVES. Field agreed to treat these and to mail them confidentially to members only for consideration and follow-up discussions. Thus all countries would have equal part in development of report and recommendations. The meetings at Duxbury and Needham, September 9-11, would be for the purpose of initial discussion. Ogilvie suggested that if a future meeting were held in Ottawa plans should be made to visit some of the Canadian mines.

Thom thought that the matter of development of resources of any one continent must have much in common with that of another--largely dependent on geological theory and geophysical practice. There should be interested students and groups in various parts of the world. Meinesz agreed and expressed the opinion that knowledge of economic geology would be furthered by the creation of an International Geological Union making for continuity of combination with geophysical applications which are often neglected by mining companies in geophysical explorations. The geophysical data acquired by various mining companies require scientific consideration to bring them back into the background with tectonophysics. IUGG must have a large part and share in this subject and should be stressed in meetings of CSVES. In the future there should be more intensive cooperation between geologists and geophysicists and stronger ties should be developed. At present the geophysical background of geology is not generally recognized; at present physicists in general are not acquainted with geological work and vice versa. Field, Thom, and Fleming made the point that perhaps the approach of IUGG and other geophysical bodies is too much from academic viewpoint. Three needs for development include problems of (1) fundamental geophysics, (2) fundamental geology, and (3) problems of the ordinary citizen and his anxieties. As one helpful measure Meinesz suggested desirability that future congresses of geophysicists and geologists be contiguous.

The following letter, for transmittal to all countries through presidents of National Research Committees or equivalent organizations, was approved:

"The Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics strongly recommends that the governments of all nations represented in that Union assist in any manner possible in furthering the observation of the Earth's field of gravity over oceanic areas. Since a submarine is necessary for this investigation it is requested that the respective navies furnish such vessels upon occasion.

"Comparatively little is known of the gravity field of oceanic regions representing over two-thirds of the Earth's surface. The information to be so obtained is essential for geodetic purposes to determine the shape of the Earth which is now only well known on continental areas where measurements of arcs in latitude and longitude are possible.

"Measurements of gravity at sea are also of great importance to geologists and geophysicists studying the causes and mechanics of earthquakes and deformations of the Earth's crust."

Commission on Continental and
Oceanic Structure, IUGG
By R. M. Field, Chairman
Jno. A. Fleming, Secretary

The action on the investigation of radio-wave velocities and the form of letter relating thereto were approved finally.

Following a rising vote of thanks to Noel J. Ogilvie for the facilities and courtesies extended to the Commission at Ottawa, the meeting was adjourned at $11^h\ 23^m$.

Jno. A. Fleming, Secretary

DISCUSSION OF

"THE EARTHQUAKE AND SEISMIC SEA WAVE OF APRIL 1, 1946"
BY RALPH BODLE
[Trans., v. 26, pp. 464-465, 1946]

Austin E. Jones (Rogue River, Oregon, November 20, 1946)--In the same issue of the Transactions that contained the above article, the writer noted several articles on oceanography that indicated a general interest in all problems of that kind. There could be a more complete tie-up of the sciences by establishing several combined oceanographic and seismographic stations and the institution of a warning service for tsunami, storms, [See "Reference" at end of discussion, GILMORE, 1946] and volcanic eruptions.

The tidal-wave of April 1, 1946 reached the Hawaiian Islands apparently without warning. Yet in 1923 and 1933 the Hawaiian Volcano Observatory had predicted probable tidal-waves. Some property could have been saved in 1923 if people had believed the warning; however, in 1933 as a result of watchfulness along the coasts, much was saved.

The proportion of the number of tidal-waves to the number of great earthquakes that occur under the oceans in different localities is unknown but should be investigated. Some years ago N. H. Heck and the United Coast and Geodetic Survey put out a catalog listing damaging tidal-waves and their occurrence was highly variable.

Certain kinds of seismograph stations can indicate the direction to the centers of large storms. The two kinds of predictions should be valuable enough to warrant the expenditure of considerable sums of money for the establishment of seismograph networks over wide areas where shipping and shore property would be endangered. Such stations could be combined with oceanographic and volcanic observatories and should cooperate with science generally. In order that the network cover the northeast Pacific Basin adequately, the writer would suggest two stations in Hawaii, three on the Pacific Coast of the United States, and three on the coast of Alaska, perhaps more if the Bering Sea is included. In order to watch the western Pacific closely, more stations would be needed on the various island groups of that region.

Reference

GILMORE, M. H., Microseisms and storms, Bull. Seis. Soc. America, v. 36, pp. 89-119, 1946

DISCUSSION OF

"REDUCTION OF WIND DATA"
BY RONALD L. IVES
[Trans., v. 27, pp. 474-484, 1946]

Arnold Court (1901 23rd St., S. E., Washington, December 6, 1946)--Wind, being the only vectorial quantity directly observed in meteorology, poses more computational problems than any other element. While a monograph on the reduction and representation of wind data is sorely needed by modern climatology, Ives' comments are generally too incomplete and in some cases too much in error to fill the gap, even partially. Specifically, mistakes appear in the explanations of "dynamic" and "resultant" winds, and exception is taken to the completeness or propriety of the mention of "sampling error," "ambient winds," "constancy," and "wind roses." Because there is, unfortunately, so little information available on wind computation, it is felt advisable to correct these misstatements.

Dynamic wind--Foremost of the errors is in the discussion of "dynamic winds," (p. 479). Distinction must be made between the dynamic pressure of the wind, $(\rho v^2)/2$, and its total power, $(\rho v^3)/2$. Dynamic pressure, as explained in standard works on aerodynamics [see "References" at end of discussion, MILLIKAN, 1941, p. 25], is the pressure produced by bringing to rest particles of a fluid of density ρ originally moving with a speed v. The energy of the wind is the product of this pressure by the distance through which it is applied. And the power of the wind is this energy per unit time, or the dynamic pressure times the speed with which it acts, that is, $(\rho v^3)/2$ [SISSENWINE, in press].

Thus Ives is confused in his entire discussion of "dynamic wind, computed by taking the square root of the sum of the squares of the individual reported speeds," and errs completely in saying (p. 483) that "dynamic winds determine the amount of power necessary to run a windmill." This amount of power is proportional to the cube of the wind speed [BROWN, 1940, p. 648; SCHUBAUER, 1945].

If the wind pressure is of interest, then the family of "dynamic winds" (total, average, resultant, and equivalent resultant) may be of value. But a study of the "work-doing ability" of wind must be based on a family of "potential winds," derived from $(\Sigma v^3/n)^{1/3}$.

Resultant wind--In declaring (p. 477) that "resultant wind is the vector sum of the reported winds during a given period," Ives violates current meteorologic practice. The resultant wind is "the vectorial average of all wind directions and speeds at a given place for a certain period, as a month" [THIESSEN, 1946, p. 225]. Discussions usually speak not of the resultant wind as such, but of the resultant direction, which is unaffected by averaging, and the resultant speed, or, improperly, velocity. "To obtain the resultant velocity, the (resultant) distance must be divided by the number of observations" [U. S. WEATHER BUREAU, 1942, p. 45]. In this division, calms are excluded [CONRAD, 1944, p. 105]. (Note: In U. S. Weather Bureau practice, calms are included.--Ed.) Thus Ives has confused resultant travel (or distance or movement or run) with resultant wind.

Except for this error, the explanation offered for the arithmetical method of obtaining resultant, due originally to Lambert and still called by his name [CONRAD, 1944, p. 101; THIESSEN, 1946, p. 174), is acceptable. But the example could be improved if it followed the style of Weather Bureau Form 1124-A [U. S. WEATHER BUREAU, 1942], which shows all multiplication factors and eliminates the confusion of negative signs by using four colums instead of two. For most places in the United States, and generally in the region of Prevailing Westerlies, it is preferable to consider North and West the positive directions, as in WB 1124-A, rather than North and East, as Ives does.

A different graphical method of summarizing wind data, particularly applicable when winds are reported to 32 or 36 directions, as are upper air winds, has been used by the writer with considerable success. Briefly, the method involves plotting each observation on a sheet of polar coordinate paper, by placing a dot in the proper direction and at a distance proportional to the speed as is done in hodograph analysis. After all points are plotted, distances of each from the two axes are read off in turn, using an engineer's scale held perpendicular to first one axis, then the other. A convenient scale on paper which has ten circles to the inch is one inch for five mph of surface wind, or ten mph of upper air winds. These four sets of distances are added, opposites are cancelled, and the components of the resultant wind travel remain. These components, divided by the number of observations, give the components of the resultant wind, which may be combined graphically or arithmetically to give the resultant direction and speed.

For greatest efficiency, the method requires two persons, one to read data while the second plots, then the second to scale off distances while the first totals them on an adding machine. The method is much faster than any other when the original data are reported to 16 or more directions. The maximum number of dots which can be placed conveniently on one sheet is somewhat over 100 --four observations daily for a month.

Ambient wind--Since the term "ambient" is used generally by physiologists, engineers, and bioclimatologists to mean outdoor or free-air conditions, a specialized "redefinition" of "ambient winds" to mean variable or opposing is regrettable. The proposed definition should be rejected, unless a considerable body of previous usage can be marshalled; Ives offers no references to support any of his proposals. If the arithmetical difference between total and resultant travel, or between average scalar and vectorial winds, is of importance, it could be given a different name, perhaps "vagrant wind" or "errant wind." However, this difference is of little value unless coupled with one of the values from which it is derived. Furthermore, it does not appear to be as useful a measure of wind variability as the generally-used persistence.

Persistence--The brief mention and curt dismissal of this ratio, between the vectorial and arithmetical sums or averages of wind travel, is hardly in keeping with its extensive use in climatology. The ratio, termed by Ives the "directional constance," is better known as the "steadiness" [CONRAD, 1942, p. 74; CONRAD, 1944, p. 106; TREWARTHA, 1943, pp. 108-113] or "persistence" [HAURWITZ and AUSTIN, 1944, p. 45]. It is often used in climatic tabulations as a convenient measure of the dispersal of the winds around the resultant, and is called "an important characteristic of wind conditions" [CONRAD, 1944, p. 189]. While this ratio may not "give any true indication of compensating or multiple shifts of wind taking place between observations," Ives offers no criterion which does afford such an indication--nor is he likely to find one, short of tabulating the wind for each minute (or second) of each day.

Sampling error--That Ives finds a "sampling error" of 20 to 35 per cent between wind speeds measured at hourly intervals and the total measured travel, over 5000 hr, is so surprising as to be hardly credible, at least without much more explanation and discussion than he offers. Neither text nor diagram (Fig. 3) states explicitly whether speeds measured each hour for a one minute interval were greater or smaller than the total movement for the hour (preceding, succeeding, or circumadjacent?). (Note: This is explained somewhat more fully by Ives in a paper now being prepared for publication in the Transactions. It appears that Court may not understand that this sampling error is the average for each hour. The net error over 5000 hours will be much less.--Ed.)

Without detailed descriptions of instruments, methods of observation and computation, corrections applied, and variations of the "errors," discussion of their cause is obviously futile. It is even more futile, without proving the case, to mention repeatedly that many tabulations use "extrapolated wind travels, rather than the actual travels," expecially since wind data from most first order Weather Bureau stations are based on automatic records, not hourly observations, and are thus "wind travel."

Accuracy of readings--A paper which attempts to correct misconceptions in the use of wind data, by an author repeatedly critical of the usual methods of wind measurement, is hardly justified in reporting two of 24 hourly speed readings (Table 1) to half-miles per hour, or 11 of 31 values (Table 5) to tenths of a mile per hour. Few cup anemometers are accurate to more than the nearest mile per hour; in this connection, Ives might have followed his own suggestion and indicated "the type of instrument used, the speed-timing method, and the height of the anemometer above the ground."

Wind roses--A wind rose has been defined [U. S. WEATHER BUREAU, 1938, p. 108] as "1. A diagram showing the relative frequency and sometimes also the average strength of the winds blowing from different directions in a specified region. 2. A diagram showing the average relation between winds from different directions and the occurrence of other meteorological phenomena." Restricting himself entirely to definition 1, Ives does not mention nephic, thermic, baric, allobaric, pluvial, and other wind roses. And he neglects entirely other forms of the wind rose, and methods of representing wind data, such as the Baillie rose [MET. OFFICE, 1940, p. 218], the octagonal rose [SHAW and GARBETT, 1933, p. 39], the 16-sided "wind star" [SHAW, 1933, p. 165], and the "clothes line," for representing north-south and east-west components at various levels [SHAW, 1942, p. 272].

No attempt is made here to cite the voluminous literature on anemology in foreign languages, nor older English references. These notes are intended merely to correct certain misstatements, and to provide a few references on the climatic representation of wind.

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TREWARTHA, GLENN T., An introduction to weather and climate, New York, 1943.

U. S. WEATHER BUREAU, Instructions to marine meteorological observers, Circular M, Washington, 1938.
U. S. WEATHER BUREAU, Instructions for making pilot balloon observations, Circular O, 1942.

Ronald L. Ives (Indiana University, Bloomington, Indiana, February 20, 1947, Author's closure)--Court, in his comments, brings out a number of interesting points in connection with the application of wind data. A number of the other points raised by Court are in the general field of semantics: a field in which widely-divergent opinions can be held, which can be supported by citing equally divergent authorities. Solution of these problems of nomenclature, which are becoming increasingly acute as the various branches of science expand and overlap, awaits formation of, and action by, an interscience committee on nomenclature. Until such a committee acts, and its rulings are accepted, correctness or incorrectness of word-usage depends upon whether or not author and reader have obtained their vocabularies from the same sources.

A redefinition of Dynamic Wind, to prevent confusion of several similar terms with the theoretical values, seems in order.

(a) A theoretical power term, based on the cube of the speed, in general accord with physical theory, as outlined by Court.

(b) A practical "work done" term, which is approximately a major fraction of a constant times the speed squared, as determined by the amount of sand piled on the road by a windstorm, or similar means.

(c) A wind force term, based on the square of the speed.

The use of the windmill analogy in this context was perhaps confusing. Investigation of the discrepancy between (a) and (b) above was halted by the end of hostilities, work done only indicating that turbulence was one of the important factors to be considered.

The great discrepancy commented upon by Court between wind speed extrapolated from a one-minute sample to give a travel figure and that determined by actual measurement of one hour's travel is apparently characteristic of high-altitude deserts. The discrepancy is notable in the Utah and Arizona deserts; is much less in the High Plains (Limon, Colorado) and still less in humid areas near the sea (Caldwell, New Jersey). A relation between the degree of this discrepancy and the frequency of occurrence of dust-devils is suggested by field observations.

DISCUSSION OF

"RADIAL FLOW IN A LEAKY ARTESIAN AQUIFER"

BY C. E. JACOB

[Trans., v. 27, pp. 198-205, 1946]

Raphael G. Kazmann (Ranney Method Water Supplies, Columbus, Ohio, August 8, 1946)--This paper is a distinct contribution to ground-water hydrology. It extends the quantitative side of ground-water research by adding a new mathematical tool to those now available to the hydrologic engineer. However, there will probably be some difficulty in applying the proposed theory; the time-drawdown curves produced by a well pumping from an aquifer that is recharged by a nearby stream are very similar to those shown in Figure 3. Assuming T = 20,000 square feet a day and a line of zero drawdown 500 feet from a well discharging at a uniform rate, Figure 1 is obtained showing how the drawdowns at distances of 200 and 500 ft from the pumped well on a line parallel to the line of zero drawdown and 500 ft from it compare with the curves computed by the author. The principal difference in form is the rate at which each curve approaches the steady-state drawdown.

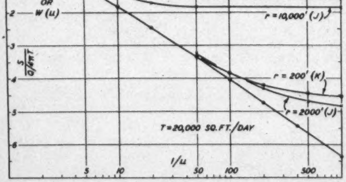


Fig. 1--Time drawdown curves produced by a leaky aquifer and by a stream-fed aquifer

When consideration is given to the difference between actual geologic conditions and the assumptions upon which the theories are based, the differences between the two types of curves are nominal and this will make it difficult to decide on the proper method of analysis. Yet, in computing the yield of a well field, the type of analysis chosen will affect the final design very much. One apparent way out of the difficulty is to confine the leaky aquifer theory to areas where there is no body of surface water to act as a nearby source of recharge. However, this may not always be desirable as is explained in the following paragraphs.

In dealing with aquifers that are recharged from nearby streams, it is customary to idealize the stream as a line source and to determine by means of preliminary pumping tests the effective distance between the pumped well and the source. However, as recharge actually occurs over an area of the stream bed, this approach must be used with caution.

A study of the author's Figure 1 reveals no substantial reason why the upper water-table sand may not be removed and a body of water substituted in its place. It should, consequently, be possible to treat the bed of a stream as the upper (and leaky) confining bed of an artesian aquifer. It may then be possible to compute K'/m' for the stream bottom and by this means to compute the ultimate maximum rate of recharge to the aquifer for given conditions of stage and temperature.

The writer believes that the "leaky aquifer" theory may prove to be a powerful tool in the solution of problems of river recharge where the "effective distance to the line of recharge" method breaks down. The leaky aquifer theory may be used where the width of a stream is small and the area of infiltration is limited. In such instances, although the effective distance to the line of recharge as determined by a pumping test at a low rate of pumping may be correct, yet when large scale production wells are installed, the area of stream bottom may prove too small to allow enough water to infiltrate to the aquifer, thus invalidating previous estimates of yield. Of course, when the nearby source of recharge is large in area, increasing the pumping rate merely increases the effective distance to the line of recharge slightly and the theory is satisfactory for practical purposes.

In short, where the area of infiltration is limited, it is of great practical importance to determine the rate per unit area at which water from a surface source will enter the aquifer. The "leaky aquifer" theory is a step toward making this determination.

In connection with the effect of the elasticity of the leaky confining bed upon the shape of the drawdown curve, the equations plainly show that the elasticity of this bed is immaterial. S' (to correspond to K' and m') never enters the equations. Regardless of whether steady or non-steady flow is involved, the confining bed acts only as a conduit, not as a reservoir. This result bears out the conclusion one would arrive at intuitively from physical considerations.

Undoubtedly the author considered his symbols carefully before using them. Nevertheless we find K and K' (permeabilities) and K_0 and K_1 (Bessel functions); T equal S Km and T which is a function independent of r. At least the latter T might have been symbolized differently.

It would be appreciated if the author would add the names of one or two texts on Bessel functions to his bibliography. I am sure that there are a number of hydrologic engineers who, like the writer, will have to "go back to school" before being able fully to follow the author's derivations.

The author should be highly commended on his very real achievement in laying the theoretical ground work for a new attack on some of the most difficult quantitative problems encountered in ground-water hydrology.

C. E. Jacob (U. S. Geological Survey, Washington, D. C., Author's closure)--In his discussion Kazmann points out the desirability of extending the concepts formulated in the paper to apply to such a practical case as that of flow through a semipervious stream bed to a nearby well or group of wells. As always, it is necessary to make certain abstractions of reality. In some cases, however, the problem may be stated in relatively simple terms. For example, assuming that the near bank of the stream is relatively steep and that it is covered with a relatively impermeable layer, or even assuming that the water passes through the bed of the stream which is narrow relative to its distance from the well, the boundary of the aquifer may be simulated by a straight line along which the following condition obtains:

$$K dh/dn - K'h/m' = 0$$

The analogous problem in heat conduction has been worked out in standard texts on that subject. Another example for which the solution is not as readily obtained is that in which the aquifer may be regarded as comprising two parts: The landward part, of more or less uniform thickness and uniform permeability, either confined or unconfined, as the case may be; and the streamward part, lying on the far side of a line approximating the bank of the stream, of lesser thickness and confined by a semipervious layer under the bed of the stream. The width of the stream may in some cases be regarded as effectively infinite, or in other cases may be considered finite. Other examples could be multiplied. It only remains for the ingenuity of the engineer to formulate his problem in approximate though concise terms, and then proceed to find the solution. The alluvium in the Ohio River Valley at different places provides situations similar to one or the other of the two hypothetical examples I have cited.

It was not intended by the writer that the solution given in the paper be used as a "tool" to distinguish the various features of infiltration from a stream near which water-supply wells are situated. As Kazmann points out, the difference between the general form of the drawdown curve for the case worked out in the paper and that for the case in which the stream recharges the aquifer directly without any loss of head owing to an intervening semipervious layer is not marked enough to be useful. Rather, one should rely upon his knowledge of the geologic conditions gained through test drilling and other exploration techniques, though, admittedly, cases will arise in which inferences drawn from the performance of the aquifer may be found to be more trustworthy than those drawn from geologic data.

Kazmann, I believe, feels that the results of the analyses given in the paper show that the compressibility of the leaky confining bed makes no difference in the problem. He expresses this by saying that "the confining bed acts only as a conduit, not as a reservoir." It should be kept in mind, however, that the compressibility of the confining bed does not enter the equation simply because, for convenience, it was excluded from consideration. In order to approximate more nearly the actual flow in many cases this factor would have to be given explicit consideration, though, obviously, it may be lumped with the compressibility of the aquifer itself. That is the procedure that is usually followed. Here again the choice of "mathematical model" that is made will depend upon the relative magnitude of the different factors. It is not always possible to consider all of them and get a rigorous solution. We must eliminate the less important and be satisfied with those that can be successfully treated together.

To answer Kazmann's request for names of texts on Bessel's functions, I may add to the one cited by Kirkham the following: "A treatise on the theory of Bessel functions" by G. N. WATSON, Macmillan, New York, second edition, 1945; "A treatise on Bessel functions and on their applications to physics," by GRAY, MATHEWS, and MACROBERT, Macmillan, London, 1931; also "A course of modern analysis," by E. T. WHITAKER and G. N. WATSON, Macmillan, New York, American edition reprinted 1945. There are others. Tables of Bessel's functions are given in these texts, but for the benefit of those who may not have them at hand, I am giving below sufficient values of the modified function of the second kind of zero order for use in plotting the "type-curve."

Table 1--Values of the modified Bessel function

x	$K_o(x)$	x	$K_o(x)$	x	$K_o(x)$
0.01	4.721	0.10	2.427	1.00	0.421
.02	4.028	.20	1.753	2.00	.1139
.03	3.624	.30	1.372	3.00	.0347
.04	3.337	.40	1.115	4.00	.01116
.05	3.114	.50	.924	5.00	.00369
.06	2.933	.60	.778		
.07	2.780	.70	.661		
.08	2.647	.80	.565		
.09	2.531	.90	.487		

The troublesome problem of nomenclature comes to the fore again. In honoring precedent one is repeatedly faced with duplications such as cited by Kazmann. Perhaps the subscripts that must invariably be associated with the Bessel function adequately distinguish them from the symbol for permeability. The uses to which T has been put should not conflict, at least directly, because they do not appear anywhere together.

The amplification of the paper by Kirkham is very helpful in giving a picture of the manner in which the solution given in the paper converges toward the other more fundamental solutions, that for steady radial flow in a bounded circular aquifer, that for steady flow in an unbounded aquifer, and that for non-steady flow in an elastic aquifer with impermeable confining beds.

The approximate relation given by Kirkham at the bottom of page 206 of his discussion [Trans., Amer. Geophys. Union, v. 26, no. 2] should permit one to extend the brief table given above.

The author desires to thank Kirkham and Kazmann for their constructive discussions.

DISCUSSION OF

"SOME FACTORS THAT INFLUENCE THE ACCURACY OF WATER-SUPPLY FORECASTING IN THE INTERMOUNTAIN REGION" By A. R. CROFT

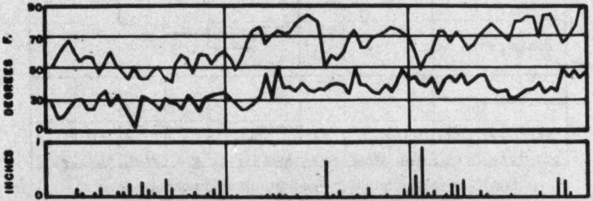
[Trans., v. 27, pp. 375-388, 1946]

M. T. Wilson (U. S. Geological Survey, Salt Lake City, Utah, October 25, 1946)--Valuable information is outlined in this paper to show many of the factors that influence the accuracy of stream-flow forecasting. Some of the assumptions and conclusions derived, however, are subject to challenge, principally because of the small area covered in the investigation and the relatively short period for which basic data were collected. Several of the factors affecting runoff could be further clarified by consideration of much basic hydrologic material being constantly obtained.

The author suggests that since many of the high water-yielding lands in the Intermountain Region have the same general characteristics, summary of results and conclusions apply also in a general way to those lands. The principle of applying runoff characteristics from one watershed to another in the Intermountain area should be accomplished with considerable caution. Factors affecting stream flow vary greatly, not only for adjacent drainage areas, but also within the confines of a small basin. This fact cannot be over-emphasized and is clearly shown by the large differences in water supply from the two small areas discussed in the paper. The phenomenon can likewise be exemplified by comparison of runoff from adjacent or nearby streams (see Fig. 1).

The Farmington Creek Drainage is on the windward side and the immediate front of the Wasatch Range, where precipitation, particularly at the lower and intermediate elevations, may be in the form of rain, while at the higher altitudes and on the leeward side snow would be accumulating. Temperatures are greatly reduced as moisture-laden air is forced to higher altitudes in passing over the mountains. Note the runoff pattern from Hardscrabble Creek which drains an area adjacent to Farmington Creek but on the leeward side. This stream did not show the large increase in flow related to rainfall as compared to snow runoff that was recorded on the windward side. In fact, as likewise shown by the other hydrographs in Figure 1 and as indicated by many stream-flow records collected over several years, this runoff characteristic as recorded in the Farmington Creek Basin is not typical. For practically all streams draining high water-producing areas the flow related to melting snow is much higher than that directly related to rainfall. Maximum stages are likely to occur when rainfall adds slightly to the snow runoff, principally by channel interception before temperatures are greatly reduced by the approaching storm. Referring to Figure 1, the increased flow for the period May 26, 1944, to June 3, 1944, was the result of higher temperatures; only for the last day or two was some increased flow related to direct rainfall. This relatively small amount was superposed on the high runoff from snow melt. The following decrease in flow was related directly to temperature changes and as shown particularly by the hydrographs of Weber River and Rock Creek, where accumulated snow was still sufficiently available, continued to follow temperature changes.

The outstanding significance of the comparative hydrographs is the diversity in runoff characteristics from streams covering a relatively small area. The different stream-flow patterns can be largely accounted for by the amount of snow cover still remaining in the basin at any chosen time. When the heavy precipitation occurred during the early part of June, 1944, there was no snow cover left on the Whipple Drainage (see the author's Fig. 3), gravitational water in the soil mantle was partly depleted, and consequently the additional stream flow was relatively small. On the Miller Drainage about ten per cent snow cover (about five per cent of the total for Farmington Creek Drainage as noted by the author) was still available. Rain on this snow, which was obviously high in water content, very likely aided in the melting of the remaining snow and thus added materially to the runoff. In fact, it is possible that most, if not all, of the snow cover at this intermediate elevation was removed by the storm. It is therefore presumptious to show on a hydrograph stream flow related to melting snow versus that related to direct rainfall, since the two cannot be satisfactorily separated. By applying this analysis to a drainage basin where less of the snow cover has been removed, a different stream-flow pattern would be anticipated. Unquestionably the Chalk Creek Drainage falls in this category, since runoff continued to advance by increasing temperatures after the storm period. Precipitation on part of this snow cover was absorbed by the snow or fell in the form of snow, as the yield did not reach the magnitude previously recorded by melting snow, which was the outstanding effect in the Farmington Creek Basin. Continuing the same reasoning to the other extreme as shown by Weber River and Rock Creek, where the percentage of snow cover still remaining at the time of the storm was large, practically all of the rain was absorbed by the snow or fell in the form of snow. Only the marginal areas of the snow fields were sufficiently primed by high temperature for producing maximum stream flow, and these rates were soon reduced by lowering temperatures accompanying and following the storm.



Maximum, minimum temperature and precipitation at Coalville, Utah.

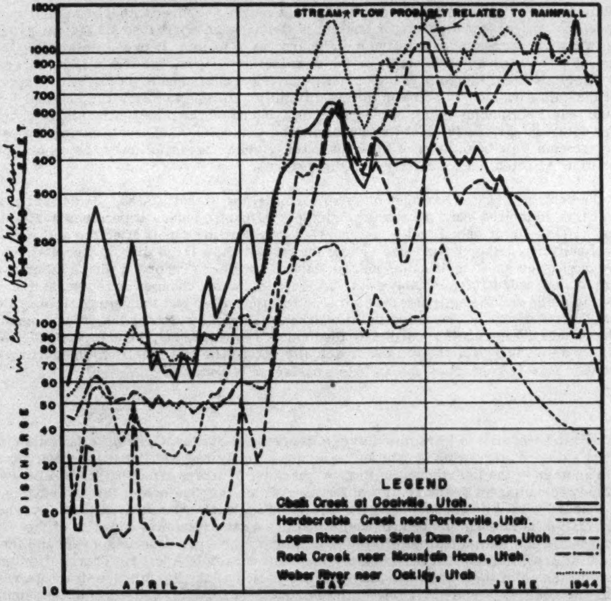


Fig. 1--Variation in stream flow as related to temperature and precipitation

The statement by the author that the high quantities of rainfall during May and June are quite unusual deserves some qualification. Long-time precipitation records for the northwestern part of Utah show that the months of March, April, and May provide the greatest moisture, whereas the months of June and July have the least (see Fig. 2). During 1944, precipitation for the month of May was slightly below normal, whereas that for the first part of June was unusually high. It is obviously this normal distribution of precipitation that makes the forecasting of water supplies based only on the measurements of water content in the snow on April 1 so subject to gross errors, as two of the largest precipitation months are yet to follow. If precipitation for this period is greatly above or below normal, or the distribution very unusual as in 1944, forecasts will be seriously affected. Since it is important to have forecasts made not later than April 1, it seems that the only satisfactory solution to this difficulty would be to follow the original forecast on May 1 and June 1 with adjustments when necessary, based on the latest climatological and stream-flow data. In spite of the fact that precipitation was contra-seasonal, during the early part of June, stream flow from most of the high water-yielding areas followed the normal pattern of snow runoff as affected fundamentally by temperatures.

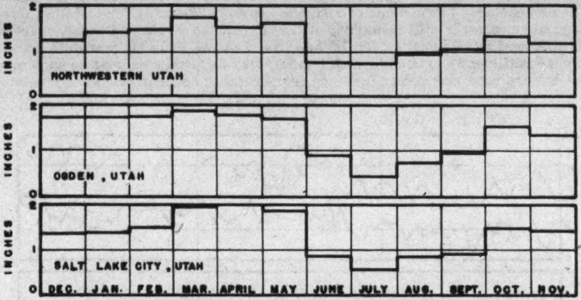


Fig. 2--Average monthly precipitation for northwestern Utah, Ogden, and Salt Lake City, Utah

Under the subject of water storage in the soil mantle, the author states, "Practically all water from rains or melted snow passes through the soil mantle before it becomes available for stream flow." This factor should not be interpreted as retarding runoff after the soil mantle has reached field capacity. Many water-stage recorder graphs show large diurnal fluctuations in stream flow during the snow-melting period. Instances have been recorded where the daily change in discharge has exceeded 100 per cent, owing entirely to diurnal changes in temperature. The rapid change in stage and the time interval between the snow field and the gaging station clearly indicate that the water was not retarded in the soil mantle before reaching the stream channel. Also see the rapid rise in runoff recorded by the author's hydrographs, Figures 2 and 5. Whether the water flows as a sheet over the ground or actually enters the soil mantle is insignificant in so far as stream flow is concerned unless it is satisfactorily retarded.

A. R. Croft (Intermountain Forest and Range Experiment Station, Ogden, Utah, Author's closure)--Wilson's discussion begins by cautioning against "applying runoff characteristics from one watershed to another in the Intermountain Region" because "factors affecting stream flow vary greatly, not only for adjacent drainage areas, but also within the confines of the same basin." The writer concurs with Wilson in the dangers of attempting such extensions, expecially when specific information is lacking on such important factors as the retention-capacity of the soil mantle, the amount of precipitation that enters the soil prior to the April 1 snow survey, and the amount and timeliness of precipitation that occurs after the snow survey of April 1. That the writer's paper was a discussion of these factors, and not an extension of the Farmington drainage runoff data to other watersheds, is stated clearly in the introduction (p. 375), and again in the summary and conclusions (p. 386).

The reason these factors have general application to forecasting stream flow from watersheds of the Intermountain Region is because (1) watersheds are covered, either completely or in part, with a soil mantle that retains relatively large quantities of water and, (2) most of the rain and melted snow-water that reaches streams in the springtime passes through the soil mantle--a phenomenon that can not take place until the water content of the soil has been raised to field capacity.

Wilson disagrees with the writer's conclusion that the secondary peak in the Farmington Creek hydrograph on June 1 was caused by the timely occurrence of an unusually heavy rainfall and a soil mantle previously nearly saturated. Wilson presents hydrographs of streams in the Wasatch and Uintah Mountains together with precipitation and temperature data from Coalville, Utah (elevation 5571 feet) to show that the high secondary peaks of these streams on about June 1 are related to temperature changes and not to precipitation. Frequent reference is made to snow cover, but no data on snow are presented to substantiate the alleged effects of temperature and snow melting on stream flow.

The basins Wilson refers to cover only a relatively small area (about 150 miles between extremes) but their location in space evidently is a minor factor in relation to stream flow as compared to the difference in the elevational range of the basins. Weber River and Rock Creek have their origin among the cirques and glacial lakes of the high Uintah Mountains, occupying elevational ranges that are 2000 to 3000 feet higher than the Logan, Chalk, and Hardscrabble drainages (Table 1).

Table 1--Elevational range and watershed area

Drainage	Approximate elevational range above gaging station		Area
	from	to	
	ft	ft	sq mi
Rock Creek near Mt. Home, Utah	7250	12,500	149
Weber River near Oakley, Utah	6700	11,500	163
Logan River above State Dam near Logan, Utah	4600	9900	218
Hardscrabble Creek near Porterville, Utah	5500	9200	25
Chalk Creek above Coalville, Utah	5600	9000	253
Lost Creek near Croydon, Utah	5800	8200	133
East Canyon Creek near Porterville, Utah	5600	10,000	145
Farmington Creek above Farmington, Utah	5000	9200	10

This difference in elevation places the two groups of watersheds in what is recognized as distinctly differenct climatic conditions and one is not surprised to find, therefore, that their hydrographs are not uniform, but have markedly different patterns.

Hydrographs of the high Uintah Mountain watersheds, Weber River, and Rock Creek, trend upward in June (as does the temperature at Coalville) but those of Logan, Chalk, and Hardscrabble, streams that drain from much lower elevations in the Wasatch Mountains, trend sharply downward in June. Though substantiating climatic and soil moisture data are not available, the continued rise of the two streams from the Uintah Mountains after May 26 suggests that those basins had a snow mantle which released more and more water to augment stream flow as the temperature increased. The downward trend of stream flow in the other basins suggests the snow mantle on them had already disappeared or was insufficient in amount to prevent the recession of stream flow during the period of rising temperatures.

Stream flow from the latter three basins, as well as from several others of comparable elevational range, was strikingly similar during the period April 1 to June 30 to that from Farmington drainage (see Fig. 1). Whatever may have been the cause of discharge fluctuations in the other basins, climatic records within the Farmington Watershed clearly suggest that the June peak of that stream was due to the coincidence of rainfall on a wet soil mantle rather than to high temperatures and melting snow. Comparison of five distinct periods of rising or falling stream flow with climatic records show where the effects of temperature were important and where this factor was obscured by the occurrence of precipitation.

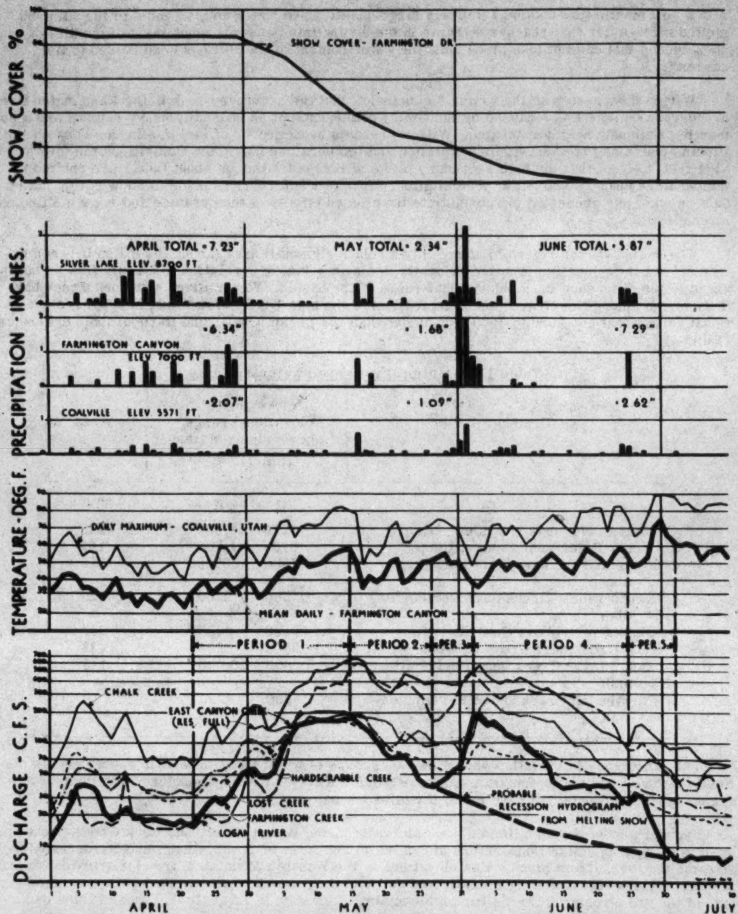


Figure 1--Some stream flow, temperature, precipitation, and snow-cover relationships, 1944

Period 1--During the period April 22 to May 15, 1944, discharge and temperature show marked upward trends. The area covered by snow decreased from 84 to 42 per cent, and three inches of rain fell before April 30. Melting snow was, no doubt, the major factor in the flow increase.

Period 2--During the period May 16 to 27, 1944, discharge dropped sharply from 175 to 38 cfs. Temperature dropped sharply for two days, heralding a rain of 0.8 inch and then made an erratic but marked upward trend that reached to within seven degrees of the previous mean daily high on May 15. The area covered by snow decreased from 42 to 24 per cent. Because stream flow continued to decrease during this period of increasingly warm temperatures and reduced area of snow coverage, it seems reasonable to assume that the early pattern of the recession hydrograph had been definitely established.

Period 3--In this six-day period from May 28 to June 2, 1944, discharge quickly increased from 38 to 180 cfs. Except for a modest rise the first two days, the temperature decreased sharply to within three degrees of its previous 16-day low; and this temperature decrease occurred while discharge made its fastest rise in the three months, April to June inclusive.

In view of the sharp rise in discharge during a period of rapidly decreasing temperature and declining snow cover, the increased stream flow must be credited very largely to rains. These, beginning May 29, laid down 5.7 inches of water by June 3. Thus, in these six days there was supplied to the watershed as rain at 7000 feet elevation, more than one-fourth as much water as was stored in snow on a north-facing slope (19.8 inches) on March 28 at the same elevation. Furthermore, whereas rains blanketed the entire watershed, an average of only about 20 per cent of it received water from melting snow during this six-day period and the water yield from melting snow no doubt decreased greatly because of the rapidly falling temperature. A very important additional fact is that the soil mantle, especially that above 7000 feet elevation, was near field moisture capacity as shown in Figures 5 and 6 of the paper. This allowed much of the rainfall to enter the soil as free water and become available for stream flow. These facts leave little doubt that the secondary discharge peak of June 2 was largely a phenomenon related to precipitation, without which, the recession hydrograph would have continued the downward trend established in Period 2.

During this six-day period Hardscrabble Creek which, as Wilson states, lies a few miles southeast of Farmington Drainage, increased its flow a little over 100 per cent. The flow of Logan River, Chalk, East Canyon, and Lost Creeks, all of which have about the same or slightly higher elevational range in the Wasatch Mountains as Farmington Drainage, increased 170, 50, 150, and 60 per cent, respectively.

Period 4--This period from June 3 to 25, 1944, is marked by a general recession of stream flow with the hydrograph showing about the same general slope as that just prior to the heavy rains near June 1. Temperature trend was erratic but upward, there being practically no relation between the frequent short temperature changes and the flow of the stream. Snow was gone on June 20, but gravitational water remained in the soil mantle for nearly four weeks as a result of the heavy, early June rains, as was shown in Figures 5 and 6 of the paper. It seems reasonable to assume, therefore, that much of the stream flow that occurred from June 5 to July 25 came directly from this temporary storage in the soil mantle and from the aquifers beneath the mantle.

Period 5--This period from June 26 to July 2, 1944, is marked by a sharp increase in flow and then a rapid decline to almost constant flow. With the snow gone and most of the soil in a very dry condition, rainfall of one inch reversed a sharp downward trend in discharge and delayed for about two days the rapid recession that began about three days before the storm.

The relation of the measured climatic and soil moisture conditions to stream flow of Farmington Creek described above leave little room for doubt that the recession hydrograph of Farmington Creek would have been a fairly smooth curve after May 15, except for the occurrence of the unusually heavy rainfall in early June.

Regarding the effect of spring precipitation on streamflow forecasts, Wilson states, "If precipitation for this period is greatly above or below normal, or the distribution very unusual as occurred in 1944, forecasts will be seriously affected." Although it is true that spring precipitation may account for large amounts of runoff, it does not necessarily follow that forecasts will be seriously affected each time unusual departures from normal spring rainfall occur because this is only one of the factors, largely unknown to the forecaster, that influence water yield. Another very important one is the moisture content of the soil mantle for it can modify greatly the yield of water from the overlying snow pack and also from spring precipitation.

Runoff from Logan, Ashley, and Weber drainages was 90, 53, and 86 per cent of forecast, respectively, in 1943; and 114, 130, and 133 per cent of forecast in 1944 (see Table 2). Spring precipitation deviation as shown by a group of stations of the United States Weather Bureau on the windward and leeward sides of these drainages was about the same in May and June both years, but in April, 1943 it was 80 per cent normal and in the same month the next year it was 206 per cent normal. These departures from normal precipitation in April do not seem sufficiently large to account for the forecast errors on Weber and Ashley drainages after allowing for a reasonable forecasting error of ± 10 per cent. Soil moisture difference in 1943 and 1944 seems to be the only plausible way of explaining the wide spread in forecasts on these two drainages in 1943 and 1944.

Runoff from Farmington drainage and its tributaries, following spring rains from May 15 to June 15, was one fifth to three times greater from a relatively wet soil in 1944 than from a considerably drier soil in 1943, not withstanding that rainfall during this period was about equal both years, as shown by Table 3, here, and Figures 3 to 6 of the paper.

Table 2--Forecast and actual runoff, thousands of acre feet, April-September

	1943			1944		
	Forecast	Actual	Per cent of forecast	Forecast	Actual	Per cent of forecast
Logan River at Logan, Utah	190.0	173.9	90	85.0	96.8	114
Ashley Creek near Vernal, Utah (50 miles east of Rock Creek)	100.0	53.0	53	65.0	84.8	130
Weber River at Oakley, Utah	156.0	134.0	86	105.0	140.3	133

Table 3--Precipitation departure from normal in inches

Station	Elevation	April		May		June	
		1943	1944	1943	1944	1943	1944
	ft						
Coalville, Utah	5571	+ 0.07	+ 0.99	. . .	- 0.11	+ 1.52	+ 1.90
Farmington, Utah	4267	- 0.82	+ 2.75	- 1.75	- 0.56	+ 2.70	+ 2.47
Laketown, Utah	5988	- 0.25	+ 0.98	- 0.95	- 0.75	+ 0.89	+ 1.47
Logan, Utah	4778	+ 0.16	+ 2.97	- 0.55	- 1.09	+ 2.06	+ 2.69
Salt Lake City, Utah	4260	- 0.67	+ 2.81	- 1.06	- 0.22	+ 1.25	+ 2.51
Silver Lake, Utah	8700	- 1.46	+ 3.54	+ 0.13	- 0.66	+ 6.00	+ 3.49
Vernal, Utah	5335	. . .	+ 0.95	- 0.35	- 0.04	+ 1.06	+ 1.00
Duchesne, Utah	5520	- 0.02	+ 0.89	+ 0.35	- 0.11	+ 0.55	+ 0.42
Evanston, Wyoming	6860	- 0.14	+ 0.59	- 0.45	- 0.31	+ 1.03	+ 1.39
Border, Wyoming	6085	- 0.43	+ 1.11	- 0.05	0.00	+ 0.97	+ 2.26
Average per cent normal		80	206	70	76	320	310

Seasonal fluctuation of soil moisture suggests the extent to which this factor may affect water yield, especially from the April snow pack. Water removed from a six-foot soil mantle each summer by evaporation and transpiration was as high as 14 inches or an average moisture deficit of more than two inches per foot of soil, as shown by Figures 3 to 6 of the paper, all of which must be replaced before any appreciable quantities of water can pass through the soil mantle to streams.

Because of the influence of soil moisture in modifying runoff from snow and rain, it is probably responsible for greater errors in streamflow forecasting than any other single factor.

The final point of this discussion has to do with the way water from melted snow reaches stream channels. In Wilson's discussion of the writer's statement, "Practically all water from rains or melted snow passes through the soil mantle before it becomes available for stream flow," he states, "This factor should not be interpreted as retarding runoff after the soil mantle has reached field capacity. . . . . Instances have been recorded where the daily change in discharge has exceed 100 per cent owing entirely to temperature. The rapid change in stage and the time interval between the snow field and the gaging station clearly indicate that the water was not retarded in the soil mantle before reaching the stream channel."

The writer concurs in Wilson's statement regarding the large daily changes in discharge as a result of melting snow, but not in his explanation of the phenomenon. Measurement of the area of the extensive system of channels and gullies (most of which are dry in summer) yielding water from a 1600-acre snow-covered watershed on the west face of the Wasatch Plateau in central Utah showed that such diurnal fluctuation was caused largely by channel interception of melting snow in the day and the absence of melting at night.

Continuing the above reasoning, Wilson states, "Whether the water flows as a sheet over the ground or actually enters the soil mantle is insignificant in so far as stream flow is concerned unless it is satisfactorily retarded." Does Wilson actually mean that water from a given point reaches a stream just as fast by passing through the soil as it does by flowing directly over the surface of the Earth? If this is the meaning, a fair question would be: Why do streams continue to flow long after all snow has melted?

DISCUSSION OF

"REPORT OF THE COMMITTEE ON EVAPORATION AND TRANSPIRATION, 1945-1946" by H. G. WILM

[Trans., v. 27, pp. 720-725, 1946]

R. W. Gerdel (Cooperative Snow Investigations, U. S. Weather Bureau, Sacramento, California, December 5, 1946)--The report on the studies of evaporation from snow surface at the Rocky Mountain Forest and Range Experiment Station indicates the need for intensive research on apparatus and procedures before reliable data can be obtained. Seasonal evaporation from the 500 square-foot pan is reported as varying in individual years from 1.33 to 2.75 inches of water. For the spring season, evaporation from the small weighing pans was smaller than from the large volumetric pans.

CHURCH, [see "References" at end of discussion, 1934] using small weighing pans, reported monthly evaporation from snow at Lake Tahoe of 1.035 to 1.745 inches for temperatures between 22.°0 and 40.°1 F. At Marlette he found evaporation losses of 2.43 inches for March with a mean temperature of 34.°1 and 0.529 inches for December with mean temperatures of 31.°8. HORTON [1914] reported a 30-day evaporation loss of one inch for "low" temperatures. The experimental procedures and apparatus used by the several investigators do not permit differentiation between evaporation losses attributable to meteorological phenomena and those losses which may be induced by the artificial conditions associated with the apparatus and procedures used.

In order to devise an evaporation experiment which would either reduce to a minimum the effect of the apparatus used, or permit the qualification of this effect, a series of preliminary studies has been made at the Central Sierra Snow Laboratory, operated cooperatively by the United States Weather Bureau and the United States Engineers. It was found that copper-clad electrical resistance thermometers frequently indicated temperatures varying from 33°-38° F at depths of two to twenty inches below the snow surface. This phenomenon could be attributed only to the absorption of long wave radiation by the copper sheath of the resistance thermometer. Subsequent experiments with chromium-plated sheaths did not indicate a material reduction in absorption of long wave radiation at depths of twelve inches below the snow surface. Studies, with highly sensitive thermocouples attached to copper plates which were supported in small cavities in the snow, indicated that measurable long wave radiation was transmitted to depths of sixteen inches. The depth to which radiation penetrated appeared to be influenced by the density and the free water content of the snow.

These experiments indicated that metal evaporation pans would have to be more than twenty inches in depth to eliminate the effect of melting from the bottom of the sample and that metal sidewalls would produce a boundary effect, resulting in a free water content and evaporation opportunity greater than in the natural snow pack. Some observations with plastics indicated that heat entrapment frequently occurs when radiation penetrates a transparent plastic in contact with a snow surface, resulting in a higher than normal melting rate. A pigmented or reinforced plastic sufficiently rigid to permit the construction of an evaporation pan may absorb as much radiation as metal of equal strength.

Intensive research at the Central Sierra Laboratory on the water-holding capacity of a snow pack indicates that the thermodynamics of free water in the snow pack is similar to that for soil moisture. When a short core of snow is contained within an evaporation pan, even though suspended on a porous plate to permit drainage as described by Wilm, there is a definite restraining influence on percolation at the interface of snow and air at the bottom of the core. This has been observed frequently in the water-holding capacity studies. A previously saturated, twenty-four inch column of snow has been found to hold more free water when the base of the column is separated from the natural snow pack, than when the bottom of the column is placed in good physical contact with the original snow pack from which it was removed. The increase in available free water within the short column of snow used for evaporation studies provides, by means of capillary potentials, increased available water on or near the snow surface with greater evaporation opportunity.

Any procedure used in evaporation studies must not neglect consideration of the relationship between the energy gradient within the snow pack due to gravity and that due to capillary tension. An example of the increased quantity of water which might be available for evaporation, in a short core of snow contained in a small evaporation pan as used by Wilm, is shown in the results of the soil lysimeter experiments reported by WALLIHAN [1940]. During a fifty-six day experiment with several lysimeters containing soil cores of 30-inch depth, there was five times as much percolate from the lysimeters to which a tension of 136 cm of water had been applied as from those without supplementary tension. Evaporation from the lysimeters without supplemental tension was much greater than from those with the additional tension applied. We may infer from this experiment that a core of snow 30 inches in depth may have five times as much water available for evaporation as one 85 inches in depth. Such great differences probably are not encountered in snow packs since the capillary potential may be much less and the rate of percolation much greater in snow than in the type of soil used in these lysimeters.

Results of these preliminary studies at the Central Sierra Snow Laboratory indicate that an ideal evaporation experiment must be so designed that the absorption of long-wave radiation by the apparatus used will not influence, materially, the amount of water available for evaporation within the snow pack. The experiment also must be so designed that normal equilibrium between capillary and gravitational potentials is maintained. It is apparent that it will be difficult to design satisfactory apparatus and procedures which will produce reliable data on evaporation from snow surfaces. It is possible that the best approach to the evaluation of evaporation from snow-covered basins of varying exposure, topography and vegetal cover will be to include this factor as one of the residuals after analyses of more reliable data for precipitation, runoff and other meteorological phenomena.

References

CHURCH, J. E., Evaporation at high altitudes and latitudes, Trans. Amer. Geophys. Union, pp. 326-351, 1934.

HORTON, ROBERT E., Evaporation from snow and errors of rain gages when used to catch snowfall, Mon. Wea. Rev., v. 42, pp. 99-100, 1914.

WALLIHAN, ELLIS F., An improvement in lysimeter design, J. Amer. Soc. Agron., v. 32, pp. 395-404, 1940.

H. G. Wilm (Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, Author's closure)--Gerdel has commented on several of the important problems involved in sampling evaporation from snow, and has pointed out some of the weaknesses in any empirical approach to these problems. After reviewing the report on our Fraser experiments in the light of his discussion, it seems that our statements might have been improved if they had included a little more detail on objectives and methods.

First as to objectives. What we wanted was to design a portable pan which might be used to sample evaporation in field experiments. These experiments are set up on forest-covered plots in mountainous country, so that such a field sampling instrument needed to be simple, compact, and easy to use. Because a large number of samples would be necessary, the instrument had to be inexpensive and portable. It was not necessary that the instrument should provide an unbiased estimate of evaporation, but only that values obtained by its use should be highly correlated with the true rates of evaporation from snow. Our plan was to measure these true rates at a single place by means of a more costly and unportable, but relatively unbiased method. At this place we could calculate the regression of evaporation as sampled by the small instruments on the measured "true" rates, thereby largely removing any bias associated with the small instrument. This is obviously a simple adaptation of the "double-sampling" method commonly used in biological research. For the inexpensive and portable instrument we tried the small metal pans described in the report. The results from these were expected to be biased, but we hoped they would be highly correlated with evaporation as measured by means of the largest pan.

In the larger, "volumetric" pans, particular effort was devoted to the avoidance of substantial instrumental bias. In order to cut down border effects, the largest pan is 500 square feet in area, about 25 feet in diameter. The metal floor of this pan is inclined toward the center at a grade of two per cent. As nearly as we could figure the probable hydraulic gradient and height of water "perched" in the pan, it was thought that this gradient, plus an exterior rim height of six inches, should confine within the pan most of the drainage water from the superimposed column of snow. In order to minimize the height of this "perched" water, drainage openings are provided not only at the center of the pan, but also at four additional points, just outside a concentric ring enclosing the center 100 square feet of the pan (see Fig. 2, p. 724 of paper). In order to balance any hydraulic gradients leading into and out of the pan, the ground outside the exterior rim was sloped away from the pan at a two per cent grade.

Gerdel makes an excellent comment on the absorption of long-wave energy at considerable depths below the snow surface. This is an important point and must be considered, expecially if it is desired to study snow evaporation rates, isolated from the influence of such energy absorption. While we had no quantitative data on the depths of snow to which such absorption might occur, we feared that it might be a factor worth considering. For this reason we did not leave the black-painted metal floor of the large pan in direct contact with the snow. Instead, we covered it with a layer of undecomposed lodgepole pine needles which was level on top. Hence it varied in thickness from about 1/2 inch at the exterior rim to about three to four inches above the center drainage openings. Thus, as nearly as possible, energy absorption conditions on the pan resembled those of the natural litter-covered soil in a pine forest.

Aside from these points, our methods contained several defects which are summarized on page 725 of our report; these are yet to be overcome before we can attain the original objectives of our studies.

DISCUSSION OF

"NOTE ON THE FREQUENCY DISTRIBUTION OF GEOTHERMAL GRADIENTS"

by H. LANDSBERG

[Trans., v. 27, pp. 549-551, 1946]

H. Cecil Spicer (U. S. Geological Survey, Washington, D. C., September 30, 1946, published with permission of the Director, U. S. Geological Survey)--The paper was read with interest and the author's purpose was commendable, but the statistical analysis of the temperature data was apparently made without consideration and study of the basic information from which the tables in the Handbook of Physical Constants [see "References" at end of discussion, SPICER, 1942] were prepared.

The introduction to the tables in the reference cited [SPICER, 1942, p. 280] specifically states that the observations of temperature have been reduced by the method of least squares to equations of the form, $T = a + bx$

where T is the temperature (°C) at the depth x, in km. It further states, that for observations in the United States, this reduction has been made for three ranges of depth: from 30.5 to 305 m (100-1000 ft), from 30.5 to the deepest observation, and from 610 m (2000 ft) to the deepest observation. Furthermore, Landsberg has apparently overlooked this statement on the same page of the reference cited: "These intervals will only accidentally bear any relation to the geological structure or stratigraphy."

The headings in Table 19-1 of the same reference are clear in stating that the "Mean thermal gradient (b) °C/km" is subdivided into three ranges, 30.5 to 305 m, 30.5 m to deepest observation, and 610 m to deepest observation. Landsberg has incorrectly used the ranges as 30.5 to 305 m, 305-610 m, and > 610 m. This incorrect application of the tabulated data invalidates much of his argument because the geothermal gradient for 305 to 610 m will obviously differ from the one tabulated for 30.5 m to deepest observation.

Landsberg could not be expected to know the geology associated with the geothermal measurements, for this material has not been published. But, from first-hand familiarity with the data, this writer knows that the observations in the United States were taken mainly in oil fields and only about two per cent were in mines; also, with the exception of two Earth temperature measurements in Georgia [VAN ORSTRAND, 1939, pp. 143-144], the temperature measurements were obtained in sedimentary formations.

The two geothermal gradients in cols. 4 and 5 of table 19-1 were given to show the type of depth-temperature curve the constants represent [VAN ORSTRAND, 1934, pp. 989-1021]. If the values are the same, the depth-temperature curve is linear; if col. 5 is greater than col. 4, the geothermal curve is convex to the depth axis; if col. 5 is less than col. 4, the geothermal curve is concave to the depth axis. The geothermal gradients in the last column are representative of values that are practically free from all surface effects. In the compilation of the Handbook, the editors, because of limited space, had to choose between explanation of the tables and the content of the tables. The latter was considered more important and the interested reader must refer to the literature cited for a more complete explanation.

In conclusion, it is felt that Landsberg's hypothesis concerning the cause of the observed geothermal gradients is based on incorrect assumptions and hence is not acceptable. It is hoped that at some future time a complete presentation of Earth temperature data containing all available basic observations and computations will be possible.

References

SPICER, H. CECIL, Observed temperatures in the Earth's crust, in Handbook of physical constants, Geol. Soc. Amer., Special Paper, no. 36, 1942.

VAN ORSTRAND, C. E., Temperature gradients, problems of petroleum,geology, Amer. Assoc. Petr. Geol., 1934.

VAN ORSTRAND, C. E., Observed temperatures in the Earth's crust, in Internal constitution of the Earth, v. 7, McGraw-Hill, 1939.

H. Landsberg (5127 27 Road North, Arlington, Virginia, Author's closure)--Spicer properly calls attention to an error in the original paper. The middle panel in Figure 1 of the paper should have been labeled as cases of geothermal gradients in the range from 30.5 m to the deepest observation. This error had also been kindly pointed out to the writer in a letter from Francis Birch.

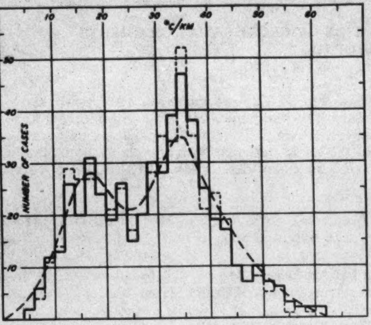


Fig. 1--Frequency distribution of 511 observations, showing bimodal distribution (revised)

To the extent that these values entered into the further deductions of the paper a re-examination of the data had to be made. From the tables published by VAN ORSTRAND [see "Reference" at end of discussion, 1939] and the many original sources given in his work the gradients were recomputed for the range from 305 to 610 m depth. The changes that had to be made in the final frequency distribution of all values are minor. They can be seen in the revised figure (see Fig. 1) which should be substituted for Figure 2 in the original paper. The frequency polygon in heavy outline gives the revised values. The dotted lines indicate the erroneous values. The summation of two normal frequency distributions fitted to the data is shown as a dashed curve. A χ^2-test for normalcy shows that the revised data actually show a slightly better fit than the original ones. The small difference between the new and the previous distribution is, in part, explained by the fact that a good many changes did not exceed the limits of various class intervals of 2° C.

This shows that the main fact presented in the original paper remains unchanged: The frequency distribution of the geothermal gradients shows two modes. The observed values vary essentially in a random fashion around these modes. No claim was made that the depth intervals bear any relation to the structure or stratigraphy. This remark in the introduction to the tables in the Handbook of Physical Constants had been noted but it has no bearing on the statistical question. Any suitable subdivision of depth intervals could have been chosen.

The hypothesis advanced to interpret the bi-modal distribution is not invalidated because most of the geothermal gradients in the United States were taken in oil fields. Fifteen per cent of the data in the frequency curve are from other countries, where many measurements were made in igneous formations. It might, however, be a better interpretation of the observations to attribute the small gradients to igneous and metamorphous rocks, and the larger gradients to sedimentary material.

In individual cases where the information is available it can be directly shown that the geothermal gradients change when a major change in lithology is encountered. For example, at Carnarvon, South Africa, shale, limestone, sandstone to 793 m depth result in a gradient of 41.°3 C/km; granite and gneiss between 793 and 1525 m depth show a gradient of 22.°1C/km. The two cases from Georgia mentioned by Spicer, where the observations were taken in gneiss fall with 13.9 and 14.°6 C/km directly into the region of the first mode of the frequency distribution. These are observations, not assumptions.

When Spicer's hope to publish all Earth temperature data in extenso is fulfilled and when more observations come to hand from a variety of formations they may provide material to consider alternate hypotheses.

Reference

VAN ORSTRAND, C. E., Observed temperatures in the Earth's crust, Physics of the Earth, v. 7, 1939.

Transactions, American Geophysical Union Volume 28, Number 3 June 1947

TWENTY-EIGHTH ANNUAL MEETING (1947)

MINUTES, GENERAL ASSEMBLY AND SECTIONS

AFTERNOON LECTURE AND BUSINESS SESSION

The afternoon Lecture and Business Session of the American Geophysical Union was called to order by President L. H. Adams at 14^h00^m, Wednesday, April 30, 1947, in the Auditorium of the Natural History Building of the National Museum, Washington, D. C. The total registered attendance at the various sessions of the Twenty-Eighth Annual Meeting was 764 members and guests.

The President introduced J. Tuzo Wilson who addressed the meeting on "Some aspects of geophysics in the Canadian Shield, with special reference to structural research." (This will be published as two papers in later issues of the Transactions.)

Following this, Richard M. Field presented a summary of the interim reports of the work of the Commission on Continental and Oceanic Structure, and the Committee on the Social Value of the Earth Sciences of the International Union of Geodesy and Geophysics [see this issue, pp. 471-472].

The minutes of the General Assembly of the Twenty-Seventh Annual Meeting were published in the Transactions [v. 27, no. 4, pp. 588-608] and were distributed to all members in good standing. They were approved as printed.

The annual report of the General Secretary (see Appendix A) was summarized briefly and accepted with thanks.

Reports of Standing Committees

Statutes and By-Laws--Chairman H. D. Harradon reported on amendments to the Statutes and By-Laws as follows: At its meeting on November 29, 1946, the Executive Committee of the Union, by unanimous vote expressed the desire that John A. Fleming, General Secretary of the Union since 1925, be elected to the post of Honorary President for life, in recognition of his long and diligent service in the upbuilding of the Union [Trans., v. 28, p. 146, February, 1947]. The Committee on Statutes and By-Laws was also instructed to determine ways and means of making such designation legal, and to proceed accordingly.

In accordance with these instructions, the Committee on Statutes and By-Laws gave full consideration to various suggestions for accomplishing the desired end and arrived at the conclusion that the post could only be made legal by inclusion in the Statutes of the Union. Accordingly the following additions to the Statutes were proposed:

To follow first paragraph, Article 5:

> There may also be elected, by mail ballot, an Honorary President whose nomination shall be tentatively approved at a meeting of the Executive Committee, followed by a mail ballot of the entire Executive Committee. A confirming vote of three-fourths of those voting shall be required to place the name on the ballot. This office shall be filled only as a special honor for outstanding service to the Union. It shall be for life without payment of dues.

To follow "ex officio" in Article 7, the words:

> the Honorary President,

> These changes were duly submitted to the vote of the Union and were adopted by a vote of 986 to 102.

He also reported concerning the review by his Committee of the Statutes and By-Laws recently submitted by the Tennessee Valley Branch, advising that no passage was found that appeared to be in conflict with the Statutes and By-Laws of the Union, and recommending their approval on this basis, recognizing the general autonomy of such branches. This recommendation was referred to the Executive Committee of the Union for action.

Membership--Chairman Irwin Roman reported on two items as follows: Including the third list of 1947, ready for the approval of the Executive Committee, election of 320 members has been recommended since the Annual Meeting of 1946. This figure excludes recommendations for transfer from associate to full membership and two recommendations for corresponding membership. In addition, 66 applications are on hand for consideration by the Committee.

Plans are actively in progress for the solicitation of corporation and regular membership applications. Your Committee can process applications and can solicit a comparatively small number of prospective members but it desires to remind you that dignified growth in membership rests with you, the 3000 members of the Union, each of whom should feel an individual responsibility in promoting the welfare and growth of the Union to the point at which our present standards may be met without asking for financial aid from other sources.

Meetings--Chairman John P. Marble reported as follows: The Twenty-Eighth Annual Meeting of the American Geophysical Union took place in Washington, D. C. on April 28 and 30, 1947. The various sections met in the Auditorium of the Natural History Building of the U. S. National Museum, in Conference Room B of the Departmental Auditorium, and in the Auditorium of the Department of Commerce. All the sections held at least one session for the presentation of papers and the transaction of business. The total registered attendance was 764. The Section of Hydrology arranged for an inspection trip to the hydroelectric installation at Safe Harbor, Pennsylvania on Sunday, April 27.

On Tuesday evening an informal Smoker was held in the Auditorium of the Cosmos Club, with no formal program. The Afternoon Lecture and Business Session of the General Assembly was held on the afternoon of Wednesday, April 30, in the Auditorium of the Natural History Building as set forth in these minutes.

An Evening Session was held on Wednesday, April 30, in Elihu Root Hall of the Carnegie Institution of Washington, at which the retiring President, L. H. Adams addressed the Union on the subject "Some Unsolved Problems of Geophysics." This was followed by the Ninth Award of the William Bowie Medal to F. A. Vening Meinesz. The citation was delivered by F. E. Wright, the Medal was presented by President L. H. Adams, and the Medal was accepted on behalf of Dr. Vening Meinesz by H. A. Helb, Counselor of the Netherlands Embassy, as the recipient was unable to be present.

A total of 115 papers and reports were presented before the various sessions, and 20 additional papers were read by title.

The Nineteenth and Twentieth Regional Meetings were held by the Section of Hydrology on the Pacific Coast, as requested by the General Secretary. Plans for the Twenty-First Regional Meeting, to be held as a general meeting of the Union in September, 1947, in New England, are well advanced.

Budget--Chairman R. M. Wilson summarized the budget proposed for fiscal year, 1948. This was referred to the Executive Committee for action. (The budget will be published in the August issue of the Transactions, with the minutes of the Executive Committee Meeting of May 1, 1947.)

Editorial and Publication Committee--Chairman J. A. Fleming summarized the activity of this Committee since the Twenty-Seventh Annual Meeting, pointing out the regular issuance of the Transactions as a bimonthly.

It was approved that the above reports be received and placed on file.

Reports of Special Committees

Tellers--Chairman Earl Ingerson reported concerning the election by mail ballot, conducted during March, 1947. The Committee met on April 8, 1947, tabulated the ballots summarized as follows:

Total number of ballots received		1195
Rejected ballots		32
Ballots without signature on outer envelope	7	
Ballots fron non-citizens of the United States	9	
Ballots mailed and received late	15	
Ballot from member in arrears with dues	1	
Qualified ballots tabulated		1163

The following officers were elected for the triennium July 1, 1947 to June 30, 1950.

Officers of the Union

President	Oscar E. Meinzer
Vice-President	H. U. Sverdrup
General Secretary	K. H. Beij

Section of Geodesy

President	H. W. Hemple
Vice-President	Harry H. Hess
Secretary	Frank L. Cully

Section of Oceanography

President	George F. McEwen
Vice-President	Edw. H. Smith
Secretary	R. H. Fleming

Section of Seismology

President	Frank Neumann
Vice-President	Perry Byerly
Secretary	Florence Robertson

Section of Volcanology

President	Wilbur S. Burbank
Vice-President	Wm. F. Foshag
Secretary	Francis G. Wells

Section of Meteorology

President	Horace R. Byers
Vice-President	Benjamin Holzman
Secretary	Woodrow C. Jacobs

Section of Hydrology

President	Lorenz G. Straub
Vice-President	F. J. Veihmeyer
Secretary	Ray K. Linsley, Jr.

Section of Terrestrial Magnetism and Electricity

President	Irwin Roman
Vice-President	J. W. Joyce
Secretary	David G. Knapp

Section of Tectonophysics

President	M. King Hubbert
Vice-President	Robert Balk
Secretary	Wilbur Burbank

Executive Committee, Section of Tectonophysics
P. W. Bridgman
James Gilluly

The results of the election on other matters were as follows: The amendment relative to the election of an Honorary President for life was carried 986 to 102, and John A. Fleming, General Secretary, was elected to that position by an even greater majority. [Note: The requirement in the revised Statutes and By-Laws, calling for a confirming nomination by mail ballot of the Executive Committee, resulted in a unanimous vote of those responding.--Ed.]

With regard to the matter of giving the Executive Committee authority to proceed in the study of affiliation with the American Geologic Institute, the vote was 908 in the affirmative, 141 in the negative.

[The Special Committee of Tellers was appointed by President Adams after consultation with Section officers, as follows: E. J. Parkin and R. M. Wilson (Geodesy); R. R. Bodle and Dean S. Carder (Seismology); Delbert M. Little and Robert G. Stone (Meteorology); H.F. Johnston (Terrestrial Magnetism and Electricity); Miner Buell and E. C. McKay (Oceanography); Fred W. Cater, Jr. and David Gallagher (Volcanology); R. S. Goodridge and W. D. Potter (Hydrology); and Gordon Davis and Earl Ingerson (Tectonophysics).]

New England Meeting--Chairman R. M. Field reported that plans are progressing well, and pointing to a highly successful meeting to be held at various points in the New England area September 17-23, 1947. Various individuals, organizations, and educational institutions are cooperating fully in the enterprise.

Resolutions--Chairman Earl Ingerson presented the report of the Committee on Resolutions, and after discussion, the following eight resolutions were unanimously adopted:

(1) RESOLUTION OF THANKS TO THE SMITHSONIAN INSTITUTION

WHEREAS, The 1947 meetings of the American Geophysical Union have been materially aided by the kind provision of space and facilities by the Smithsonian Institution, therefore be it

RESOLVED, That the American Geophysical Union extend its hearty thanks to the Smithsonian Institution and request the General Secretary to express its gratitude to the Secretary of the Institution.

(2) RESOLUTION OF THANKS TO THE DEPARTMENT OF COMMERCE

WHEREAS, The Department of Commerce has kindly granted the American Geophysical Union permission to use the Auditorium of the Department, and

WHEREAS, Use of this Auditorium has contributed considerably to the success of the 1947 meetings of the Union, therefore be it

RESOLVED, That the American Geophysical Union extend sincere thanks to the Department of Commerce and request the General Secretary to express its gratitude to the Secretary of Commerce.

(3) RESOLUTION OF THANKS TO THE PUBLIC BUILDINGS ADMINISTRATION

WHEREAS, The Public Building Administration has permitted use of the Departmental Auditorium for a part of the 1947 meetings of the American Geophysical Union, and

WHEREAS, Use of this space and other facilities has been of great help in conducting the said meetings, therefore be it

RESOLVED, That the American Geophysical Union extend hearty thanks to the Public Buildings Administration and request the General Secretary to express its gratitude to the Director of the Public Buildings Administration.

(4) RESOLUTION OF APPRECIATION TO THE CARNEGIE INSTITUTION OF WASHINGTON

WHEREAS, The Carnegie Institution of Washington has for many years extended facilities to the American Geophysical Union in the provision of space for office and storage at the Department of Terrestrial Magnetism, and

WHEREAS, The Institution is now providing excellent facilities in its Administration Building, and

WHEREAS, These provisions have very greatly facilitated the work of the Union, and

WHEREAS, The operating expenses of the Union have been materially reduced thereby, therefore be it

RESOLVED, That the American Geophysical Union express its grateful appreciation to the Carnegie Institution of Washington for the continuation and extension of these most helpful facilities, and be it further

RESOLVED, That copies of this Resolution be sent to the President of the Carnegie Institution and to the Chairman of the Board of Trustees.

(5) RESOLUTION ON TIME-SIGNAL SERVICE

WHEREAS, There is a vital need in all astronomical, geodetic, magnetic, and seismological work for accurate time service, and

WHEREAS, The time service maintained by the United States Naval Observatory, the Naval Communications Service, and the National Bureau of Standards has been of great use in this work, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation of this valuable scientific cooperation, and be it further

RESOLVED, That copies of the Resolution be sent to the Secretary of the Navy, the Director of Naval Communications, the Superintendent of the Naval Observatory, the Secretary of Commerce, and the Director of the National Bureau of Standards.

(6) RESOLUTION ON USE OF THE METRIC SYSTEM

WHEREAS, The use of the metric system is widespread in scientific work, and

WHEREAS, At the present time many organizations in this country engaged in making geophysical surveys or preparing maps regularly use the United States customary units in describing stations or making maps, and

WHEREAS, The American Geophysical Union recognizes the benefits of using the metric units in map making and in geophysical surveying, therefore be it

RESOLVED, That the American Geophysical Union urge that all organizations, both public and private, engaged in geophysical surveying or in map making use the metric system whenever it is suitable for the intended use. It is specifically recommended that published results be in metric units in all cases where these are for the use of geophysicists and other scientists. The inclusion of equivalent values in U. S. customary units for the convenience of nonscientific users is a matter to be left to the judgment of the issuing agency.

(7) RESOLUTION ON GROUND-WATER STUDIES OF THE GEOLOGICAL SURVEY

WHEREAS, The House of Representatives by its action on the Interior Department appropriation bill for 1948 has eliminated the study of ground water by the United States Geological Survey, thus taking action to terminate functions of great scientific and practical value which the Federal government has exercised for the last fifty years,--functions which have been thoroughly demonstrated as being of vital national importance in peace and in war, therefore be it

RESOLVED, That the American Geophysical Union, in its Annual Meeting, April 28-30, 1947, express sincere regret at this action and strongly urge the Congress to provide for the continuation of essential ground-water work of the Geological Survey as heretofore, and be it further

RESOLVED, That copies of this Resolution be sent to the members of the Senate and House Appropriation Committees of the Congress.

(8) RESOLUTION ON OPERATION CROSSROADS

WHEREAS, The members and guests of the Section of Oceanography of the American Geophysical Union have appreciated greatly the symposium on the oceanographic results obtained during Operation Crossroads, therefore be it

RESOLVED, That the American Geophysical Union express its appreciation and thanks to the Chairman of the Joint Crossroads Committee for the opportunity, encouragement and support that the Commander of Joint Task Force gave to the oceanographers who participated in that undertaking.

In addition, one resolution from the Section of Meteorology (relating to the long and faithful service of H. D. Harradon, as Secretary of the Section) was read for the information of the Union and one (relating to budgetary matters) was referred to the Executive Committee for action regarding its proposal.

Cooperation with International Commission for Study of Tidal Waves--Chairman E. C. McKay reported that this Committee has been inactive because of the inactivity of the International Commission which has not yet resumed activity in the postwar period. He recommended if the International Commission is not to resume activity, that this Committee be disbanded. It was approved that the incoming officers give this matter their consideration in the reappointment of Committees. Chairman McKay added further that the report of the Committee in 1946, relative to the Seismic Sea wave of April 1, 1946, resulted in a more extensive analysis of the data by the U. S. Coast and Geodetic Survey as obtained from its tide gage records, and the preparation of a special chart showing the seismic sea-wave travel times to Hawaii.

Geophysical and Geological Study of Ocean Basins--Chairman H. H. Hess summarized the report set forth in Appendix B.

Geophysical and Geological Study of Continents--Chairman W. T. Thom, Jr. communicated the report presented in Appendix C.

Time-Signal Service--Chairman Paul Sollenberger's report is summarized in the Resolution (5) on Time-Signal Service, indicating that cooperation in this work has continued through the year 1946-1947.

Cosmic-Terrestrial Relations--Chairman Harlan T. Stetson summarized the report presented in Appendix D.

Award of the William Bowie Medal--Chairman Walter H. Bucher reported the unanimous agreement of the Committee on the recipient named for the Ninth Award (F. A. Vening Meinesz).

Affiliation with the American Geological Institute--Chairman W. T. Thom, Jr. reported as follows: Since the meeting of the Union's Executive Committee on November 29, 1946, a referendum of the American Geophysical Union membership has resulted in a vote of 908 to 141, empowering the Executive Committee to make a decision for, or against Union affiliation with the proposed American Geoligical Institute. The situation with respect to formation of the Institute has also been significantly changed by action of the American Association of Petroleum Geologists, which has voted to adhere to the Institute. This, we believe, makes the roster of organizations which have voted adherence run as follows:

In Favor of Adherence

American Association of Petroleum Geologists
American Institute of Mining Engineers
Society of Economic Paleontologists and Mineralogists
Society of Exploration Geophysicists
Society of Vertebrate Paleontologists

It is our impression that the Canadian Institute of Mining Engineers is also favorable to adherence. The Paleontological Society of America, and Mineralogical Society of America, are postponing their decisions until the Geological Society of America has come to a decision--the Geological Society's recent action, on advice of counsel, having been to postpone any decision until such time as the American Geological Institute shall have been formally incorporated. We do not have information as to what action has been taken by the Seismological Society of America.

The Constitution of the Institute as proposed, and other pertinent material were mailed to members in February, 1947 in connection with the ballot. Other documents, including a statement prepared by a Committee of the Council of the Geological Society of America, and a memorandum by Allen Membard, legal advisor to the Geological Society, have been placed in the Unions files.

Metric System--Chairman L. V. Judson communicated word that the report of the Committee is summarized by Resolution (6) on the Use of the Metric System.

It was approved that the above reports of special committees be received and placed on file.

New Business

The President emphasized importance of the work of the Membership Committee, pointing out that there are still many well-qualified persons who are not now members of AGU. To attain the goals of service to geophysicists and to geophysics in general, many of these must be brought into the membership. This is largely the responsibility of the individual members, as it is possible for the Membership Committee to know relatively few of the prospective members.

Harry H. Hess offered the following motion and comment:

> I move that the Union officially express to John A. Fleming, retiring General Secretary, its sincere appreciation for his splendid work during the past 22 years. Few men have given so much to a cause so unselfishly. The successful growth and development of the AGU is very largely due to his efforts. Any words which I can think of would be quite inadequate to express what we all feel as John A. Fleming retires.

This motion was seconded and unanimously passed by a rising vote, with applause.

Adjournment--Meeting was adjourned at 16^h50^m.

Sessions of Sections--The minutes of the meetings of the Sections of the American Geophysical Union, April 28 to April 30, 1947, are given in Appendices E to M.

EVENING LECTURE SESSION

The Evening Lecture Session of the General Assembly was called to order in Elihu Hall, Administration Building, Carnegie Institution of Washington, 1530 P Street, Northwest, Washington, D. C. on April 30, 1947 at 20^h40^m by Vice-President Walter H. Bucher, who presented the speaker of the evening, President L. H. Adams. The subject of Dr. Adams' Presidential Address was "Some Unsolved Problems of Geophysics." (It is anticipated that this address will be published in a later issue of the Transactions.)

Following this, the Vice-President turned the chair over to the President, who then presented Frederick E. Wright. Dr. Wright made the citation of F. A Vening Meinesz who was named the recipient of the Ninth Award of the William Bowie Medal by the Special Committee on the Award. Response and acceptance was made on behalf of Dr. Vening Meinesz by H. A. Helb, Counselor of the Netherlands Embassy. The citation by Dr. Wright, the response by Mr. Helb, together with the reply and acceptance by mail from Dr. Vening Meinesz, are printed on pp. 359-360 of this issue of the Transactions.

The President then declared the Meeting adjourned, and an informal social hour followed in the foyer adjacent to the Hall. About 150 members and guests were in attendance.

APPENDIX A--REPORT OF GENERAL SECRETARY OF AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-EIGHTH ANNUAL MEETING, APRIL 30, 1947

Membership--During the period from May 28, 1946 to April 25, 1947, the Union's membership has grown from 2727 to 2966, a net growth of 239, and with over 60 applications for membership now in the hands of the Membership Committee, the total membership may be considered to be in excess fo 3000. There are still many qualified persons who are not members of AGU, and the aid of every member is enlisted in offering opportunity to these to become members.

Since May 28, 1946, the deaths of 13 members have been reported, as follows:

Eliot G. Mears (May 27, 1946)
Harry C. Dukes (June 22, 1946)
A. E. Staniland (June 28, 1946)
F. W. Stiefel (July, 1946)
Oskar T. Dauelsberg (September 15, 1946)
G. F. Loughlin (October 22, 1946)
H. H. Clayton (October 27, 1946)
Gleason W. Kenrick (October 29, 1946)
Wm. A. Mattice (October 29, 1946)
Alfred C. Gregory (November 30, 1946)
Warren N. Thayer (December 5, 1946)
David E. Stephens (December 14, 1946)
Henry G. Avers (January 19, 1947)

F. A. Vening Meinesz has been elected a Corresponding Member of the Union, bringing the total to five. There are now 18 life members of the Union.

Executive Committee Meetings--The Executive Committee held three meetings during the last year, one on May 28, 1946, immediately following the Business Meeting of the Twenty-Seventh Annual Meeting [see Minutes, Trans., v. 27, pp. 608-613, August, 1946], one on October 25, 1946 [see Minutes, Trans., v. 27, pp. 903-915, December, 1946], and one November 29, 1946 [see Minutes, Trans., v. 27, pp. 145-147, February, 1947]. In addition to administrative and financial matters, special attention was given to matters relating to election procedures in connection with the first election of officers by mail ballot. The results of this ballot appear in these minutes as the report of the Committee of Tellers.

Meetings--The Nineteenth Regional Meeting of the Union was held by the South Pacific Regional Committee of the Section of Hydrology in Pasadena, California, February 15, 1947. About 100 members and guests attended. The Twentieth Regional Meeting was held in Portland, Oregon, April 21 to 23,by the North Pacific Regional Committee of the Section of Hydrology, jointly with the Western Snow Conference, and the Columbia Basin Water Forecast Committee. The Twenty-First Regional Meeting will be held in New England, September 17-23. This meeting will be a General Meeting of the Union.

The Twenty-Eighth Annual Meeting of the Union, held April 28-30, 1947, in Washington, D. C., had a total registered attendance of 764. Its success was the result of the energy of the Committee on Meetings under the Chairmanship of John Putman Marble.

Branches--The Tennessee Valley Branch held an Organization Meeting on March 21, 1947, which President L. H. Adams attended as guest speaker. Their proposed Statues and By-Laws are being presented to the Executive Committee for action.

Publications--The Transactions have been issued at regular bimonthly intervals during the last year, and sent to all members in good standing as well as to subscribers. The Transactions of 1946 (v. 27) comprised 926 pages. On pages 303 to 357 of the issue of April, 1947 is a list of members as of March 10, 1946. This is the first list published since October, 1943. It is the plan to list new members in each succeeding issue of the bimonthly.

Statutes and By-Laws--Changes in the Statutes and By-Laws have been reported by the Standing Committee.

Finances--An audited financial statement for Fiscal Year 1946 was published in the Transactions [v. 27, pp. 766-768, October, 1946]. At the end of Fiscal Year 1947, a statement for the year will be submitted promptly to the Standing Committee on Audit.

The National Research Council made an allotment of $400 to the Union for the year ending June 30, 1947. The balance of the grant from the Rockefeller Foundation has been received in four-equal quarterly payments. The total grant has been $20,000 for the three years, 1944-1947.

The $5000 special publication fund has been received from the R. E. Horton Estate and is being utilized for the completion of certain of Dr. Horton's manuscripts as provided.

International Union of Geodesy and Geophysics and related bodies--Walter D. Lambert attended the meetings of the International Council of Scientific Union, the International Union of Geodesy and Geophysics, and the International Associations of Geodesy held in England and France during the summer of 1946. At the Extraordinary General Assembly of the IUGG held in Cambridge, England, in August, 1946, plans were laid for a General Assembly of that Union to be held in Norway in

September, 1948.

Activity of these international organizations has been increasing during the last year, and Articles of Agreement have been drawn up regarding the relations between the International Council of Scientific Unions (ICSU), and UNESCO has given a sum of $27,431 in support of the work of the ICSU.

The American Geophysical Union sent two representatives (John Putman Marble and W. F. G. Swann) to a National Conference on UNESCO held in Philadelphia, Pennsylvania, March 24-26, 1947, and three representatives (C. A. Heiland, A. H. Koschmann, and H. S. Riesbol) to a similar conference in Denver, Colorado, May 15-17, 1947.

Office of Union Moved--In January, 1947, the office of the Union was moved from the Department of Terrestrial Magnetism, Carnegie Institution of Washington, at 5241 Broad Branch Road, N. W., where it had long been quartered, to splendid, centrally located quarters in the Administration Building of the Carnegie Institution of Washington at 1530 P Street, N. W.

Other activities--The Union has aided the National Roster in preparing a vocational booklet entitled "Geophysics as a Profession." This is to be released very soon, and copies may be secured by addressing the Superintendent of Documents, or the National Roster, Washington 25, D. C.

The Union was represented by C. L. Garner at Fourth Assembly of the Pan American Institute of Geography and History, and the Third Pan American Consultation on Cartography, in Caracas, Venezuela, August 22 to September 1, 1946; by Bradford Willard at the installation of the new president at Lehigh University on October 20, 1946; by William E. Wrather at the Second Pan American Congress of Mining Engineering and Geology held in Brazil in October, 1947.

The progress of AGU has been excellent during the year 1946-1947, and the organization has continued and augmented its service to the field of Geophysics in every possible way.

JNO. A. FLEMING, General Secretary

APPENDIX B--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF OCEAN BASINS

H. H. Hess, Chairman

Frederick Betz, Jr.
Walter H. Bucher
W. E. Dickinson
Maurice Ewing
David T. Griggs
L. L. Nettleton
C. S. Piggot
Francis P. Shepard
D. C. Skeels
Paul A. Smith
Harlan T. Stetson
T. Wayland Vaughan

Summaries of those research projects which would be best suited to advance the special objectives of this Committee, have been given in preceding reports and will not be repeated in this report. In this, the first post-war year, the Committee has made notable progress towards furthering its research aims.

In November, 1946, the Hydrographic Office, U. S. Navy published the bathymetric chart of the area from Korea to New Guinea (HO 5485) which represents a marked achievement in the field of the Committee's interests. A similar chart covering the area from New Guinea to New Zealand is under construction. While these charts are supplied as general charts to ships of the U. S. Navy and Merchant Marine, they also are being constructed with the aim of making a fundamental contribution to science. For this farsighted policy the Hydrographic Office is to be commended. Fifteen years of cooperation between the Hydrographic Office and this Committee have borne fruit for both parties.

The Committee has drawn up detailed plans for completion of the gravity at sea net along the north coasts of Colombia and Venezuela (see Fig. 1). Ewing reports that he has been able to obtain funds from the Office of Naval Research which assure carrying out of an extensive program of gravity work at sea for the next eighteen months. The work planned for the continental shelf along the Atlantic coast of North America and for the southern part of the Caribbean will probably be completed this summer. Plans for expansion of gravity at sea work into other areas and for testing of new instruments and techniques are under way. The gravity work at sea will be under the direction of Ewing. The Committee will continue to serve in an advisory and planning capacity as needed.

B

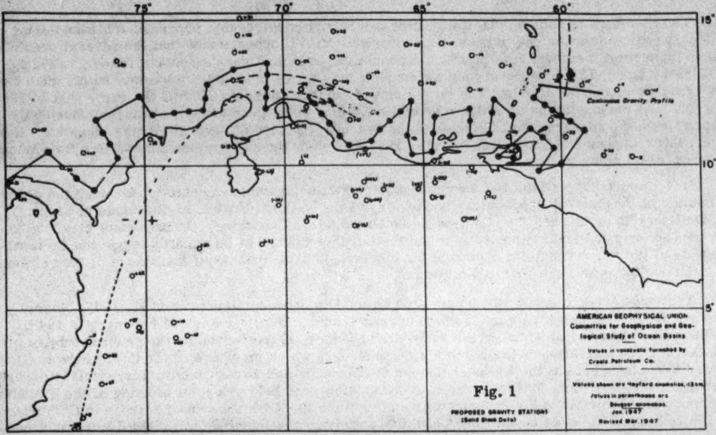

75°
70°
65°
60°
15°
10°
5°
Continuous Gravity Profile
AMERICAN GEOPHYSICAL UNION
Committee for Geophysical and Geological Study of Ocean Basins
Values in Venezuela furnished by
Creole Petroleum Co.
Values shown are Hayford anomalies, 113 km
Values in parentheses are
Bouguer anomalies.
Jan. 1947
Revised Mar. 1947
PROPOSED GRAVITY STATIONS
(Solid Black Dots)

Fig. 1

Among the most notable achievements during the year within the field of this Committee's interests are: (1) The seismic profile obtained by Dobrin, Snavely, White, Beresford, and Jenkins across Bikini Atoll, and (2) the determination of the thicknesses of sediments above a reflecting layer in the Atlantic Basin south of Bermuda by Hersey and Ewing.

APPENDIX C--REPORT OF SPECIAL COMMITTEE ON GEOPHYSICAL AND GEOLOGICAL STUDY OF CONTINENTS

William T. Thom, Jr., Chairman

Alfred H. Bell
Marland P. Billings
Perry Byerly
Stuart K. Clark
Nelson H. Darton
Ronald K. DeFord
Charles F. Deiss
Carroll E. Dobbin
A. J. Eardley
J. Brian Eby
Beno Gutenberg
Marshall Kay
L. B. Kellum
P. B. King
Paul D. Krynine
T. S. Lovering
J. B. Macelwane
W. G. Meyer
W. A. Nelson
L. L. Nettleton
James A. Noble
Eugene S. Perry
Alfred K. Snelgrove
G. W. Wilson, Jr.
George P. Woollard

During the year 1946-1947, regional gravitational and geomagnetic studies have been continued by G. P. Woollard, under project grants from the Geological Society of America, and in part in cooperation with the Dominion Observatory of Canada.

Attention has also been centered upon a revision of the "Basement-Surface" contour map of the Eastern and Central United States. This revised map should be ready in final drafted form by June 30, 1947. In this work, very broad and helpful cooperation has been received from many individuals and from oil and mining companies.

Formal and collaborative liaison has also been established with the Research Committee of the American Association of Petroleum Geologists, which is engaged in the development of a large and coordinated program of researches closely akin to some of those in which this Committee is actively interested. Contact has also been continued with the Tectonics Committee of the Division of Geology and Geography, National Research Council.

APPENDIX D--REPORT OF THE SPECIAL COMMITTEE ON COSMIC-TERRESTRIAL RELATIONSHIPS FOR THE YEAR 1946-1947

Harlan T. Stetson, Chairman

Charles F. Brooks
J. Howard Dellinger
Jno. A. Fleming
I. F. Hand
Frederick Hellweg
S. A. Korff
G. W. Pickard
John Q. Stewart
William T. Thom, Jr.

The members of this Special Committee can report considerable progress achieved during the past year which was one of unusual sunspot activity. It appears now that the several predictions made by several members for the next maximum stated in last year's report [Trans., v. 27, pp. 596-598, August, 1946], while in good agreement, may prove to have been too late rather than too early for the actual maximum. The large sunspot numbers during 1946 and the early part of 1947 suggest that the prediction of Waldmeier of 1947.6 may yet appear to be the closest. Much will depend upon the appearance of the peak of the secondary period of several months' duration. However, there is good likelihood that the year 1947 will show the highest sunspot average for any one year of the present solar cycle.

It is important to report that new ionospheric stations have been established under the general direction of the Central Propagation Laboratory of the National Bureau of Standards of which Dr. J. H. Dellinger is in charge. The Central Radio Propagation Laboratory, an important clearing house for ionospheric and field intensity data and the full interchange of information since the declassification of the subject matter, has made for more rapid progress of our knowledge of the relation of solar radiation to ionospheric conditions.

The large sunspot group which appeared on the Sun between March 5 and 15, 1947, closely rivaled the largest group on record which appeared during the first week of February in 1946, and was accompanied by wide-spread radio disturbances. Conferences on the general subject of the Sun and the ionization of the Earth's atmosphere, in which members of the Committee participated, have been held at the National Bureau of Standards and at the Cosmic Terrestrial Research Laboratory at Needham, Massachusetts. A symposium was held at a joint meeting of the American Astronomical Society and the American Association for the Advancement of Science in Cambridge in December, 1946, in which members of this Committee participated, and yielded important contributions to the subjects of which this Committee is concerned.

As usual, the Department of Terrestrial Magnetism under the direction of John A. Fleming, recently retired, has made important contributions to this field. Fleming calls attention to the remarkable advantages that have been made in the realization of magnetic surveys of considerable accuracy in the air. As soon as present techniques have become refined, world magnetic surveys can be accomplished in a fraction of the time required by older methods of marine and land surveys. The air technique has also the advantage of making possible, for the first time, surveys at different levels that will render a picture of the distribution of the Earth's magnetic field vertically as has never before been possible. Such results should be of considerable importance in connection with the study of cosmic rays and other cosmic effects. J. Q. Stewart, on revised calculations, now predicts the next sunspot maximum to occur in 1948.0, more closely in accord with Waldmeier's prediction of 1947.6

Charles F. Brooks has given important advice from a meteorological view point and reports that at the Blue Hill Observatory, Milton, Massachusetts, measurements of total insolation on a horizontal surface and with a direct solar beam at normal incidence have been continued through the 14 years of such records. Hourly observations of cloud amounts by kinds at high, middle and low levels and of maximum visibility in any direction have also been continued during daylight hours.

Haurwitz, associated with the Blue Hill Observatory, has published a paper "Insolation in relation to cloud type" in the Journal of Meteorology for December, 1946. Haurwitz has recently accepted the Chairmanship of the Department of Meteorology at New York University.

Computations of diffuse insolation on clear and partly cloudy days have been made by Miss S. H. Wollaston of the Observatory, resulting in values which were found to vary greatly when a given month of one year was compared to a corresponding month of another year.

Irving Hand reports that the Solar Radiation Section of the Special Scientific Services Division has begun work on the project to determine the albedo of clouds as a part of a program of scientific research organized by the Navy and carried out with the cooperation of the Army Air Forces. Records of the fluctuations in solar radiation have been received on an Eppley pyrheliometer installed in the top of the forward section of an Army B-29 and flights have already been made to altitudes of 25,000 feet. It is believed that these flights will lead to accurate evaluation of the albedos at various ground surfaces and to a better understanding of the phenomenon of the scattering of solar radiation in the atmosphere.

Solar-terrestrial research suffered a great loss in the death of Henry Helm Clayton on October 27, 1946 at the age of 85. His final paper on cycles was completed only a week before his death and has already appeared in a publication of the Smithsonian Institution. Clayton's voluminous tabulations on solar-terrestrial relationships, compiled from 1929-1946, have been presented by Mrs. Clayton to the Blue Hill Observatory Library and it is understood they will be published by the Observatory.

At the Cosmic Terrestrial Research Laboratory at Needham, the radio field intensity program has been carried on systematically and several improvements have been made. The Laboratory is now operating seven field recorders on frequencies ranging from 780 kc to 92.1 mc. Five of the receivers have been replaced with equipment which is crystal controlled in order to minimize monitoring caused by temperature drifts. Over 3000 hours of observations are collected, reduced, and evaluated monthly, and reports made to Washington.

Analysis of the night-time values from WWV 5 mc has shown a ten fold increase in the field intensities received at Needham with the rise in sunspots from 1942 to 1947. Daytime fields have decreased presumably due to increased absorption in the E layer. A change in the seasonal pattern of the diurnal variation with sunspots has been a matter of special study, details of which were reported to the Section of Terrestrial Magnetism and Electricity of the AGU.

G. W. Pickard has pursued his studies of tropospheric reception, deducing important relations between reception in the 40 to 50 mc band over a path of 167 miles to calculated atmospheric refraction. These results were presented at the Annual Meeting of the Institute of Radio Engineers and will appear in the Proceedings of the Institute at a future date.

The cosmic ray telescope, that was in operation at the Laboratory on a short-time project and on which reports have previously been made, is in the process of reconstruction so that it may be adapted for long-term records with a maximum of reliability and minimum of maintenance. In connection with this project, your Committee has had the valuable counsel of Serge A. Korff of New York University whose services have been co-opted onto this Committee during the year. It is to be noted that the Committee on Coordination of Cosmic Ray Investigations, created by the Carnegie Institution in 1932, has published its 14th and final report. With the retirement of the members of this Committee, W. S. Adams, J. A. Fleming and F. E. Wright, the administration of its uncompleted activities was delegated to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

The Laboratory at Needham has recently begun investigations of solar emissions in the lower frequencies of the radio spectrum. There has been much activity during the past year among various observers in the detection and measurement of microwaves of solar origin, commonly called "solar noise." The earlier work of Pawsey, Payne-Scott and McCredy in Australia in 1945, reported radio waves from the Sun at frequencies of 200,000 kc. Sir Edward Appleton of London and his co-workers have reported emissions of frequencies from the Sun as low as 50 mc. Similar "solar noise" has been reported received at 44.9 mc at Laurel, Maryland. These results have stimulated many others to enter the field. The Cosmic-Terrestrial Research Laboratory has, during the past year, carried on successful experiments in this direction. With a single dipole directed broadside to the Sun and tuned to 45 mc, radio bursts were observed on March 9, 10, and 13, during the passage of a very large group of sunspots. Provision for turning the dipole at an angle of 180° for a nul point made it possible to confirm the reality of the Sun as a source of origin. It appears possible that with further improvement of apparatus, scientists may yet find a new index of solar activity through the measurement of solar noise of radio wave frequencies. Unlike the usual telescope, a microwave telescope will become independent of clouds and overcasts. Systematic observations should prove of special importance to the subject of solar-terrestrial relationships.

The Chairman of this Committee takes this occasion to express his appreciation for the fine cooperation received from all of the members and the various Government agencies who have furnished material and information on every occasion requested.

APPENDIX E--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Twenty-Eighth Annual Meeting of the Section of Geodesy was called to order by the President, W. D. Sutcliffe, at $09^{h}10^{m}$, April 30, 1947, in the Auditorium, Natural History Building of the National Museum, Washington, D. C. There were 90 members and guests in attendance.

Since no corrections were received, the President declared the minutes of the Twenty-Seventh Annual Meeting of the Section of Geodesy approved as published in the Transactions [v. 27, pp. 598-599, August, 1947].

J. B. Small, representative of the Section of Geodesy on the Membership Committee of the Union, made a few remarks in regard to the membership status. He stated that in a few days each member would receive a communication requesting him to secure new members. He urged each member to canvas his personal acquaintances to see if there were some working in the field of geophysics who would be interested in joining the Union. He announced that at the present time the membership was slightly over 3000 with approximately 550 affiliated with the Section of Geodesy. The goal of the Membership Committee is to increase the membership of the Union to 4000 by 1948. He also stated that if there were any guests present who would desire to submit applications for membership, he would be glad to see them after the meeting.

C. A. Whitten, member of the Editorial and Publications Committee representing the Section of Geodesy, encouraged members to prepare discussions on any paper published in the Transactions. Such discussions should be sent to the Executive Secretary before the closing date. He reported that the Committee is preparing an index of the first 25 volumes of the Transactions.

C. J. Clifford, Chairman of the Resolutions Committee, reported that no resolutions had been submitted.

E. J. Parkin, member of the Committee of Tellers (who with R. M. Wilson represented the Section of Geodesy), reported the results of the election of officers for the Section of Geodesy for the triennium beginning July 1, 1947, as follows: President, H. W. Hemple; Vice-President, H. H. Hess; and Secretary, F. L. Culley.

The Business Meeting of the Section was adjourned, and the following scientific papers were presented:

(1) J. E. Speert: Survey net adjustment by electrical analogue
(2) B. K. Meade: Earthquake investigation in the vicinity of El Centro, California; Horizontal movement
(3) J. B. Small: Vertical movement of bench marks near fault lines in southern California
(4) E. J. Parkin: Vertical movement in the Los Angeles region, 1906-1946
(5) R. H. Montgomery: Precise leveling on the Alaska highway (read by H. S. Rappleye)
(6) J. A. O'Keefe: Errors of the doubly equidistant projection
(7) L. E. Shmidl: Simultaneous adjustment of multiple arcs of triangulation
(8) Fred Anderegg: Aerial negatives and prints, their classification and preservation in the United States
(9) Ivan Tolstoy: Punched card computation of isostatic and topographic reductions
(10) G. P. Woollard: Recent regional gravitational surveys in eastern North America
(11) J. H. Brittain: Progress in geodetic surveys by the United States Coast and Geodetic Survey since July, 1946
(12) Manuel Medina: Geodetic work accomplished in Mexico from May, 1946 to February, 1947 (read by title)

The meeting adjourned at 12^h10^m.

J. A. DUERKSEN, Secretary

APPENDIX F--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Eighth Annual Meeting of the Section of Seismology was called to order by the President, V. C. Stechschulte, at 09^h25^m, April 28, 1947, in the Natural History Building of the National Museum, Washington, D. C.

The minutes of the previous meeting were published [Trans., v. 27, pp. 599-600, August, 1946], and as no corrections or additions were received, the President declared them approved as published.

As there was no Committee on Resolutions appointed during the past year, the President called for proposed resolutions from the floor. There were none.

D. S. Carder of the Section Tellers (R. R. Bodle and D. S. Carder) reported the results of the election of officers for the Section of Seismology for the triennium beginning July 1, 1947, as follows: President, Frank Neumann; Vice-President, Perry Byerly; and Secretary, Florence Robertson.

As there was no unfinished or new business to be acted upon, the Section proceeded to the scientific papers as follows:

(1) Maurice Ewing and Frank Press: A theory of microseisms with geologic applications

(2) Ross R. Heinrich: The Ozark earthquake of October 8, 1946
(3) J. B. Hersey and Maurice Ewing: Reflection of sound from beneath the ocean floor
(4) Thomas C. Poulter: Seismic measurements on the Ross Shelf Ice
(5) Elliott B. Roberts: Some trends in seismology
(6) Frank Press and Maurice Ewing: Elastic waves in a floating ice sheet
(7) D. S. Hughes: Remote recording seismograph
(8) Anatol J. Shneiderov: On a pattern in celestial configuration in the years of major earthquakes
(9) James B. Macelwane: Progress Report for the Jesuit Seismological Association for 1946
(10) Beno Gutenberg and Charles F. Richter: Earthquake study in southern California, 1946 (read by title)
(11) Leonard M. Murphy: Geological effects on microseisms in the Caribbean
(12) J. E. Rameriz: New seismograph station at Chinchina, Colombia

The meeting adjourned at $12^{h}50^{m}$.

L. M. MURPHY, Secretary

APPENDIX G--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Eighth Annual Meeting of the Section of Meteorology was held April 28 and 29, 1947, in the Auditorium of the Natural History Building of the National Museum, Washington, D. C. About 250 members and guests were present.

The opening session was held from $14^{h}15^{m}$ to $17^{h}00^{m}$, April 28, 1947, with President F. W. Reichelderfer and Vice-President H. R. Byers presiding. The reading of the minutes of the previous meeting was dispensed with, as they had already been printed in the Transactions [v. 27, pp. 600-601, August, 1946] and no corrections or additions had been received. The President then appointed the Committee on Resolutions (L. P. Harrison, Chairman, and L. B. Aldrich) emphasizing the fact that any resolution proposed must be in the hands of the Committee in time for presentation to the Section at its morning session on April 29, 1947. He then introduced to the Section, C. M. Penner, accredited representative to the Section from the Department of Transport, Air Services, Meteorological Divison, Toronto, Canada.

J. Namias presented a brief report on the activities of the Committee on Extended Forecasting. He stated that the Committee has thus far acted chiefly in an advisory capacity. It has almost completed a bibliography of papers on extended forecasting covering the past five years which will be submitted for publication in the Transactions.

W. C. Jacobs then spoke briefly on the activities of the Committee of Climatology. He mentioned the advances made by the war agencies and quoted some of the resolutions which had been proposed by the Committee. He advocated the preparation of a source-book on climatology.

President Reichelderfer then called for the report of the Tellers (Delbert M. Little and Robert G. Stone) on the election of officers of the Section for the three-year term beginning July 1, 1947. As neither one of the tellers for the Section was present, President Reichelderfer announced the results as follows: President, H. R. Byers; Vice-President, Benjamin Holzman; and Secretary, Woodrow C. Jacobs.

At the opening of the second session, held from $09^{h}10^{m}$ to $10^{h}30^{m}$, April 29, 1947, the Committee on Resolutions presented one resolution which was unanimously adopted as follows:

(1) RESOLUTION OF APPRECIATION TO H. D. HARRADON

WHEREAS, H. D. Harradon has served for 12 years as Secretary of the Meteorology Section of the American Geophysical Union, and

WHEREAS, H. D. Harradon has rendered faithful and efficient service to the Section without stint of effort, therefore be it

RESOLVED, by the Section of Meteorology of the American Geophysical Union that the Section express its sincere and hearty appreciation to H. D. Harradon for his invaluable contribution to the success of the Section by his loyal and indefatiguable efforts.

The scientific program for the two sessions consisted of the following papers:

(1) Irving I. Schell: The Sun's spottedness as a possible factor in the polar air outbreaks in northwestern North America
(2) Arnold Court: Thermal gradient in the Ross Shelf Ice
(3) Charles S. Gilman: Large-scale synoptic aspects of forecasting freezing temperatures in Florida
(4) Robert D. Fletcher: Computation of thunderstorm rainfall
(5) C. F. Brooks: The representativeness of a climatological station
(6) V. Conrad: A contribution to the theory of relative homogeneity of climatological series (read by Malcolm Rigby)
(7) Luna B. Leopold: Status of climatological studies in the Hawaiian Islands (read by title)
(8) H. R. Byers and Collaborators: The possible use of radar in estimating the amount of rainfall over a small area
(9) N. E. Manos and W. L. Molo: A technique for a weather study of an air route
(10) R. Tousey, J. D. Purcell, J. J. Oberly, F. S. Johnson, and E. Durand: Ozone distribution from a V-2 rocket

H. D. HARRADON, Secretary

APPENDIX H--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Twenty-Eighth Annual Meeting of the Section of Terrestrial Magnetism and Electricity was held in two sessions on April 29, 1947, in Conference Room B, Departmental Auditorium, Washington, D. C.

The morning session was called to order at 09^h12^m by President H. F. Johnston. There were approximately 175 members and guests in attendance. The minutes of the previous meeting were declared approved without objection, as published in the Transactions [v. 27, no. 4, pp. 601-602, August, 1946].

The President reported that he had acted as teller for the Section in the recent election of officers. He reported the returns of the election with respect to the Section offices, and in accordance with the returns declared the following candidates elected for the triennium beginning July 1, 1947: President, Irwin Roman; Vice-President, J. Wallace Joyce; and Secretary, David G. Knapp. [For further details of the election refer to the report of the Tellers Committee for the Union, p. 497 of this number.]

In accordance with a request of the Committee of the Union on Resolutions, it was announced that any resolutions that were proposed, to be brought to the attention of the Union through that Committee, would have to be submitted to its Chairman for consideration not later than 15^h00^m, April 29, 1947. The President named a Section Committee on Resolutions consisting of O. W. Torreson (Chairman) and J. Wallace Joyce.

The President reported that the resolution adopted at the previous meeting, urging wider use of the Metric System by surveying and mapping agencies, had been brought before the Business Meeting of the Union last year, and that after some discussion, the Union had approved the creation of a special Committee on the Metric System to report on the matter to the 1947 meeting. He stated further that favorable action this year by the Committee was anticipated on a substantially similar resolution [see Transactions, v. 27, no. 4, p. 591, 1946; and v. 28, no. 2, p. 357, (the Committee on the Metric System is the unnamed one at the foot of page 357)]. [For action taken on this question subsequent to this Section Meeting, see the minutes of the 1947 Business Meeting of the Union in this number, p. 498.]

After routine announcements, the President concluded the Business Meeting by urging upon the attention of the members the important role played by each one individually in making known to his associates the advantages of membership in the Union, and in maintaining the healthy growth that has prevailed ever since the inception of the Union.

The scientific program proceeded at 09^h25^m with eight papers presented during the morning session that adjourned at 12^h41^m. The afternoon session was convened at 14^h06^m by President Johnston and was devoted to the presentation of twelve papers (paper 10 was read by title) with approximately 125 members and guests in attendance. The meeting was adjourned at 17^h48^m. The presentations were in many instances followed by active discussion, particularly in relation to papers (3), (6), (7), (12), (16), (18), and (19), summaries of which cannot be published in the available space. The presentation of papers (2) and (5), inclusive was classified and augmented by actual demonstration of the apparatus on the lecture table, including delineation of various electrical quantities by means of cathode-ray oscilloscopes. The scientific program was as follows:

(1) E. H. Vestine: Remarks on the Schrödinger unitary field theory as applied to the Earth's and Sun's permanent magnetic field
(2) L. H. Runbaugh: The properties of the saturable inductor as a detector for measuring magnetic fields
(3) E. O. Schonstedt: The orientation problem in continuously recording mobile magnetometers
(4) L. R. Alldredge: The design of saturable-inductor type magnetometers
(5) J. M. Klaasse: The correlation of magnetometer records with flight paths in aerial magnetic mapping
(6) Frank Press and Maurice Ewing: Magnetic anomalies over oceanic structures
(7) Elliott B. Robers: Problems of magnetic mapping
(8) Roland F. Beers and Harold R. Larsen: A new station-type magnetometer
(9) O. H. Gish: Atmospheric-electric phenomena at Parícutin Volcano
(10) Elliott B. Roberts: Current magnetic work of the United States Coast and Geodetic Survey (read by title)
(11) Joseph Kaplan: Some fundamental processes of geophysical interest in oxygen and nitrogen
(12) H. W. Wells: Polar radio disturbances during magnetic bays
(13) M. B. Harrington: Relations of ion density in the D region to the sunspot cycle as inferred from radio-wave absorption and variations in terrestrial magnetism
(14) A. G. McNish and J. V. Lincoln: Statistical study and prediction of annual sunspot numbers
(15) T. N. Gautier: Variability of noon values of F_2 critical frequency at different ionosphere stations
(16) A. G. McNish: Possible effects of terrestrial magnetic variations on ion density in the F_2 layer
(17) T. R. Burnight: V-2 ionosphere studies by the Naval Research Labortory
(18) E. Durand, F. S. Johnson, J. J. Oberly and R. Tousey: New high-altitude solar ultraviolet spectra
(19) G. R. Wait: The electrical conductivity of air irradiated by ultraviolet light
(20) Harlan T. Stetson: Recent studies of radio field-intensity measurements at the Cosmic-Terrestrial Research Laboratory, Needham, Massachusetts
(21) H. Herbert Howe: Magnetic measurements at Little America

DAVID G. KNAPP, Secretary

APPENDIX I--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Twenty-Eighth Annual Meeting of the Section of Oceanography was held April 28, 1947, in two sessions, in Conference Room B, Departmental Auditorium, Washington, D. C. The morning session was held 09^h25^m to 12^h45^m and the afternoon session from 14^h00^m to 16^h55^m, with President H. U. Sverdrup presiding at both sessions.

The minutes of the previous meeting were published [Trans., v. 27, p. 603, August, 1946] and no corrections or additions have been received. The President declared them approved as printed.

M. W. Buell, Jr., reporting for the Section Tellers (Buell and E. C. McKay), announced the election of the following officers for the Section for the triennium beginning July 1, 1947:-President, George F. McEwen; Vice-President, Edward H. Smith; and Secretary, R. H. Fleming.

President Sverdrup brought up the question of the Section having several standing committees. In order to give members time to consider, he suggested that action be deferred until the end of the meeting.

The scientific program consisted of a symposium on oceanographic studies in Bikini and surrounding areas. The following papers were presented during the two sessions of the symposium:

(1) P. A. Humphrey: Meteorological conditions in the northern Marshalls region
(2) K. O. Emery, J. I. Tracey, Jr., and H. S. Ladd: Submarine geology and hydrography in the northern Marshalls
(3) W. S. Von Arx: The circulation of Bikini and Rongelap Lagoons

(4) C. A. Barnes, D. F. Bumpus, and J. Lyman: Ocean circulation in the Marshall Islands area
(5) E. C. Lafond: The use of bathythermograms to determine currents in low latitudes
(6) W. L. Ford: Salinity and temperature relationships in Bikini Lagoon
(7) W. H. Munk and M. C. Sargent: Wave driven currents over shallow reefs
(8) T. S. Austin, M. C. Sargent, and D. B. Johnstone: Basic biological factors determining the rate of growth of Bikini Atoll
(9) M. W. Johnson: Zooplankton as an index of water exchange between coral lagoons and the open sea
(10) J. W. Johnson, M. P. O'Brien, and A. B. Focke: Model experiments on impulsive waves in shallow water
(11) R. Revelle, N. J. Holter, and F. G. Morris, Jr.: Some characteristics of surface gravity waves from explosions
(12) K. G. Scott and G. C. Ewing: Radioactivity tracer technique applied to measurement of large scale diffusion in the sea
(13) W. H. Munk, G. C. Ewing, and R. Revelle: Diffusion in Bikini Lagoon

The following papers, not related directly to the Symposium, were read by title:

(14) R. O. Glover: Oceanographic activities at the United States Navy Hydrographic Office
(15) J. F. Farley: Coast Guard plans for oceanographic work
(16) L. O. Colbert: Availability of oceanographic data in the United States Coast and Geodetic Survey
(17) H. U. Sverdrup: Research within physical oceanography and submarine geology at the Scripps Institution of Oceanography during April, 1946 to April, 1947
(18) H. R. Seiwell: Investigation of underwater pressure records and simultaneous sea surface patterns
(19) G. H. Keulegan and W. C. Krumbein: Stable configuration of the bottom slope in a shallow sea and its bearing on geological processes
(20) J. A. Putnam and J. W. Johnson: The dissipation of wave energy by flow in a permeable sea bottom and by bottom friction
(21) J. W. Johnson: The refraction of surface waves by currents
(22) R. G. Folsom: Subsurface pressures due to oscillatory waves
(23) A. C. Vine and Maurice Ewing: The free-falling bathythermograph
(24) Nelson Steenland: Formation surveying
(25) J. L. Worzel and Maurice Ewing: Improvements in underwater bombs
(26) M. W. Buell, Jr. and H. H. Hess: The greatest oceanic deeps

At the close of the scientific program, R. Revelle was given a vote of thanks for his efforts in organizing the Symposium.

A resolution of Thanks to the Chairman of the Joint Crossroads Committee (see Resolution 8) proposed by P. D. Trask was adopted unanimously and referred to the Business Meeting of the Union.

The question of having several standing committees was again brought before the meeting. After some discussion by R. H. Fleming and C. J. Fish, it was decided to take no formal action, the question being left open for possible future action by the incoming officers.

L. P. DISNEY, Secretary

APPENDIX J--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology was called to order by President R. E. Fuller, April 29, 1947 at 14^{h}05^{m}, in the Auditorium of the National History Building, Washinton, D. C.

David Gallagher of the Committee of Tellers (who with Fred W. Cater, Jr., represented the Section of Volcanology) reported the election of officers of the Section for the triennium July 1, 1947 to June 30, 1950 as follows: Wilbur S. Burbank, President; William F. Foshag, Vice-President; and Francis G. Wells, Secretary.

Eight scientific papers were then presented as follows:

(1) T. W. F. Barth: Geysers of Iceland
(2) E. G. Zies: The halogen content of the steam condensates from Santa Maria, Guatemala

(3) George Kennedy: Some quenching experiments with basalts
(4) Ray E. Wilcox: Activity of Paricutin Volcano from September 18 to November 30, 1946
(5) Robert R. Coates: Past volcanic activity in the Aleutian Islands
(6) D. M. Hopkins: Geology of Okmok Volcano, Umnak Island, Alaska
(7) F. M. Byers, Jr., and W. W. Brannock: Geochemical investigations of Aleutian volcanoes during 1946
(8) E. G. Zies: A program of volcanological research

All except paper 8 were accompanied by lantern slides, many of which were in color.

The meeting adjourned at 17^h15^m.

FRANCIS G. WELLS, Secretary

APPENDIX K--MINUTES OF THE ANNUAL MEETING OF 1947, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

At the invitation of John A. Walls, President of the Pennsylvania Water and Power Company, a group of 35 members and friends visited the Safe Harbor hydroelectric plant on the Susquehanna River on Sunday, April 27, 1947. The trip was arranged by Carroll F. Merriam. After an excellent luch at the Community House of the Company, brief talks on the hydrology of the watershed were made by E. T. Schuleen, W. D. Myers, and H. R. Weiler, and the party inspected the dam and the power house. On Friday, April 25, Merriam gave an illustrated talk on the Safe Harbor plant in the Auditorium of the Department of Agriculture in Washington to Government engineers including most of those who made up the party on Sunday. Copies of this talk were distributed both Friday and Sunday.

All regular sessions of the Section were held in the Auditorium of the Department of Commerce Building, Washington, D. C.

The first session was called to order at 09^h20^m on April 28, 1947, by C. E. Jacob, and the following papers constituting a Symposium on the Ground Water Hydrology of Limestone Terranes were presented:

(1) A. G. Swinnerton: Terrane conditions controlling limestone solubility--A review
(2) D. K. Hamilton: Solutional development in the blue-grass region of Kentucky
(3) W. O. George: Development of limestone reservoirs in Comal County, Texas (read by W. L. Broadhurst)
(4) D. F. Kent: Geological factors relating to solution development and underground stream flow in the East Tennessee zinc district (read by title)
(5) B. C. Moneymaker: Some broad aspects of limestone solution in the Tennessee Valley (read by title)
(6) H. H. Cooper: A deep limestone aquifer at Fernandino, Florida
(7) G. D. Roberts: Limestone problems of the Bull Shoals Dam

Discussions of these papers were lively and interesting. The session adjourned at 12^h10^m.

The second session was called to order at 14^h15^m on April 28, 1947, by the Secretary, who introduced the speaker--J. Tuzo Wilson, Professor of Geophysics, University of Toronto. Wilson's subject was Exercise Musk-Ox, an operation planned under his directorate and executed with the aid of the Royal Canadian Air Force, using ten snowmobiles and traversing 3100 miles of Arctic wastes in winter. After an interesting talk, illustrated by lantern slides, Wilson showed a motion picture which covered the entire Exercise. Because of a failure of the projection equipment, the picture was shown without sound, but this was rather to the advantage of the audience, who greatly enjoyed Wilson's extemporaneous running commentary.

The third session was called to order by Past-President N. C. Grover at 09^h10^m on April 29, 1947, as the Business Meeting of the Section. The Secretary transmitted greetings from Vice-President Straub in India, and read the following radiogram from President Church, also in India: "From Tibetan Border April 16. The Himalaya is slowly yielding to snow surveying. Forgive me for deserting you."

W. D. Potter and R. S. Goodridge, Tellers for the Section, announced the results of the elections of officers for the Section for the triennium beginning July 1, 1947: President, L. G. Straub; Vice-President, F. J. Veihmeyer; and Secretary, R. K. Linsley, Jr.

W. C. Lowdermilk, on behalf of the Honors and Awards Committee, announced the award for a first paper of exceptional merit in hydrology by a young hydrologist to Henry Walter Anderson (see Appendix L).

Three resolutions were offered and adopted unanimously. Two of these, not requiring action by the Union, are as follows:

(1) RESOLUTION OF THANKS TO THE PENNSYLVANIA WATER AND POWER COMPANY

WHEREAS, thirty-five members of the American Geophysical Union, Section of Hydrology, on Sunday, April 27, 1947, were entertained at the Safe Harbor hydroelectric plant on the Susquehanna River, and were afforded the opportunity of inspecting all features of the plant which were explained by engineers of the Company, therefore be it

RESOLVED, by the Section of Hydrology at its Annual Meeting in Washington, D. C., on April 28, 1947, that the Section extend its heartiest thanks to the Pennsylvania Water and Power Company for its hospitality, and request the Secretary to express its gratitude to the President of the Company, Mr. John A. Walls; and be it further

RESOLVED, that appreciation be expressed to Mr. Walls for the many courtesies extended by Charles G. Landis, F. W. Lowry, Carroll F. Merriam, Walter D. Myers, E. T. Schuleen, D. K. Trissler, and H. R. Weiler on the Sunday inspection trip, and further to Carroll F. Merriam for his excellent talk on Safe Harbor in Washington on Friday, April 25, 1947.

(2) RESOLUTION OF APPRECIATION TO RETIRING OFFICERS

The Section of Hydrology is mindful of the efficient service and interest of its officers, which has contributed in large part to the rapid growth of the Section and general interest in Hydrology throughout the country and in making Hydrology a science. Accordingly, it wishes to express its appreciation for the outstanding work of its officers, who are now completing a term of office that included the War period.

Therefore, the Section of Hydrology in session assembled at this the Twenty-Eighth Annual Meeting resolves that an expression of its appreciation be extended to:

(1) President Church, not only for his work as an officer of the Section but also for his leadership in developing the snow surveys of the world as evidenced by his present assignment as a consultant to the Government of India in the formulation of a program of snow surveys in the Himalayas;

(2) Dr. L. G. Straub for his efficient work as Vice-President and frequently acting President of the Section; and

(3) K. Hilding Beij, whom we especially want to honor for his long, faithful, efficient and cheerful service as Secretary of the Section of Hydrology. Mr. Beij was elected Secretary in 1933 and has served 14 years up to the present with distinction and with efficiency,and at no inconsiderable expenditure of his time and personal funds in furthering the interests of the Section.

To all of these officers we extend our deep appreciation and our best wishes.

The third resolution with regard to the Business Session of the Union and affairs as Resolutions (7) in the minutes of that Session.

There being no further business, the Business Meeting adjourned.

The following papers and reports were then presented:

(R1) S. W. Lohman: Report of the Research Committee on Ground water (read by title)
(R2) C. E. Jacob: Report of the Research Committee in Permeability
(9) R. G. Kazmann: The induced infiltration of river water to wells
Discussion by K. E. Anderson and M. I. Rorabaugh
(10) K. E. Anderson: Effect of acidizing on transmissibilities calculated by the recovery method
(11) Don Kirkham: Theory of flow of ponded water into drains in soil overlying an impervious layer (read by title)

Dr. Grover then introduced R. S. Goodridge who took the chair for the remainder of the session.

(12) C. K. Wentworth: Growth of the Ghyben-Herzberg transition zone under a rinsing hypothesis (read by title)
(13) D. J. Cederstrom: Ground water in southern Okinawa
(R3) Merrill Bernard: Report of the Research Committee on Precipitation
(14) G. D. Abrams: On the variability of precipitation in the United States

(R4) L. A. Richards: Report of the Research Committee on the Physics of Soil Moisture (read by W. O. Smith
(R5) W. C. Lowdermilk: Report of the Research Committee on Erosion
(15) C. B. Brown: Effects of land use on sedimentation in Lake Decatur, Illinois
(16) R. W. Bailey: Mud-rock flows and watershed conditions in northern Utah (read by title)
(17) W. D. Ellison: Soil detachment by water in erosion processes
(R6) P. E. Church: Report of the Research Committee on Lakes (read by title)

The session adjourned at 12^h15^m.

The fourth session was called to order by the Secretary at 14^h15^m on April 29, 1947, who introduced Merrill Bernard, Chairman of the Research Committee on Hydrologic Regions. Bernard lead the round-table discussion on Hydrologic Regions. After the discussions, a subcommittee consisting of W. C. Lowdermilk, K. L. Roberts, and one other to be appointed by them, was instructed to formulate recommendations to the new Executive Committee of the Section regarding the future of the Research Committee, these recommendations to be based on the discussion at the round-table and the data in the Committee files.

The fifth session was called to order by G. W. Musgrave at 09^h10^m on April 30, 1947, and the following reports and papers were presented:

(R7) R. C. Farrow: Report of the Research Committee on Snow (read by title)
(18) N. E. Manos and G. D. Abrams: A statistical approach to the snow-melt problem
(19) V. J. Schaefer: Changes in snow on the ground
(R8) Francois E. Matthes: Report of the Research Committee on Glaciers
(R9) R. W. Davenport: Report of the Research Committee on Runoff
(R10) L. G. Straub: Report of the Research Committee on Dynamics of Streams (read by title)
(20) W. S. Eisenlohr, Jr: Effects of water temperature on flow of a natural stream
(R11) H. G. Wilm: Report of the Research Committee on Evaporation and Transpiration (read by title)

The Chairman then introduced W. G. Hoyt who took the chair for the remainder of the session.

(R12) G. W. Musgrave: Report of the Research Committee on Infiltration
(21) Leon Lassen and E. N. Munns: Vegetation and frozen soils
(22) Leonard Schiff and F. R. Dreibelbis: Infiltration, soil moisture, and land use relationships with reference to surface runoff
(R13) C. S. Howard: Report of the Research Committee on Chemistry of Natural Waters (read by title)
(23) J. D. Hem: Fluctuations of dissolved solids concentration of some southwestern streams (read by W. W. Hastings)
(24) W. W. Hastings and W. O. George: The occurrence of nitrates in ground waters of Texas (read by title)
(R14) E. N. Munns: Report of Hydrology Sub-Committee of the Federal Interagency River Basin Committee

The session adjourned at 12^h10^m.

K. HILDING BEIJ, Secretary

APPENDIX L--REPORT OF THE HONORS AND AWARDS COMMITTEE OF THE SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION, APRIL 29, 1947

W. C. Lowdermilk

In the absence of our retiring President, J. E. Church, who is now in India consulting on the making of snow surveys in the Himalaya Mountains, I have been requested to present this report. Some three years ago the Section of Hydrology, through its Executive Committee, established two awards to be made annually, or less frequently as the Honors and Awards Committee should find it desirable to do. The Senior Award is made for a paper of unusual excellence for an outstanding contribution to the science of Hydrology. The Junior Award is made for a first paper of high merit and excellence by a young hydrologist. Selections are to be made from papers published in the Transactions of the American Geophysical Union.

This year your Committee is presenting the first award under this plan. The Senior Award is omitted for this year.

The Junior Award is hereby presented to

HENRY WALTER ANDERSON

for his paper entitled "The Effect of Freezing on Soil Moisture and on Evaporation from a Bare Soil," which was published in the December, 1946 issue of the Transactions.

Mr. Anderson is a Conservationist doing research in flood control surveys. He received his degree in Bachelor of Science from the University of California in 1943, and graduated with highest honors in forestry. He is a member of Sigma Xi and of Xi Sigma Pi. In August,1945 he became a member of the American Geophysical Union.

Anderson writes that he was unable to arrange to be present this morning to his regret and to ours as well. The award itself is in the form of an engrossed certificate which is now being prepared. Because of the absence of President Church and Vice-President Straub, who will sign this certificate as officers of the Section, it was not practicable to complete the certificate in advance. But, in due time, it will be transmitted by the Secretary to Anderson.

APPENDIX M--MINUTES OF ANNUAL MEETING OF 1947, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Tectonophysics of the American Geophysical Union was held on the morning of April 30, 1947, in Conference Room B, Departmental Auditorium, Washington, D. C. The meeting was called to order by President Cloos at 09^h00^m. The minutes of the previous Annual Meeting were approved as published [Trans., v. 27, pp. 607-608, 1946].

The report of the Committee of Tellers (Earl Ingerson and Gordon Davis) pertaining to the election of officers for the Section for the triennium beginning July 1, 1947 was presented, the results of which are summarized as follows: President, M. King Hubbert; Vice-President, Robert Balk; Secretary, Wilbur S. Burbank; and members of the Executive Committee of the Section, P. W. Bridgman and James Gilluly.

Following presentation of this report, the meeting proceded with the prepared scientific program, which consisted of the following technical papers:

(1) Ernst Cloos: Boudinage
(2) Chester R. Longwell: Development of slaty cleavage in a thrust block
(3) Francis Birch: Crustal structure and surface heat flow near the Colorado Front Range
(4) Ross Gunn: Quantitative aspects of juxtaposed ocean deeps, mountain chains, and volcanic ranges
(5) Ralph L. Miller: Overthrusting and underthrusting in the Cumberland Block, Lee County, Virginia
(6) M. King Hubbert: The mechanical basis for certain familiar geologic structures

All of the subjects presented were of considerable interest to the audience and provoked extensive discussion. It was suggested that the topic of slaty cleavage, upon which there still exists no complete agreement, would be a very fitting one for a symposium at the next Annual Meeting of the Section. The Chairman proposed that James Gilluly be asked to prepare a paper reviewing the present status of this problem and the nature of the several conflicting hypotheses concerning it. It is also hoped that prospective authors who wish to make contributions to this symposium will begin preparation of their data as soon as possible.

The meeting adjourned at 12^h30^m.

M. KING HUBBERT, Secretary

REGIONAL MEETING, SECTION OF HYDROLOGY, SOUTH PACIFIC AREA, FEBRUARY, 27 1946

The meeting in Sacramento on February 27, 1946, was one of three meetings arranged for those interested in engineering and hydrologic problems. The American Society of Agricultural Engineers met the day previous to the meeting of the Section of Hydrology, and the Western Snow Conference met the day following the Hydrology meeting.

The type of program was a departure from that usually arranged for meetings of the South Pacific area. Heretofore, papers were selected which dealt with one phase of hydrology. For this meeting, papers were invited which treated various technical problems in hydrology. Special effort was made to obtain papers from those who had not previously presented papers at the Section meetings, with particular appeal to some of the younger investigators.

The meeting was well attended. One hundred and four signed registration cards and there were a number of others who attended who did not register. Registrations showed that Oregon, Washington, Nevada, Utah, and Canada were represented.

Edward Hyatt, State Engineer of California, was chairman of the morning session, and W. J. Parsons, Jr., United States Engineer Office, was chairman of the afternoon session. Fred Paget, Division of Water Resources, State Department of Public Works, California, was in charge of the local arrangements for the meeting.

F. J. VEIHMEYER, Chairman, Regional Committee

REGIONAL MEETING, SECTION OF HYDROLOGY, SOUTH PACIFIC AREA, FEBRUARY 15, 1947

The South Pacific Meeting of the Section of Hydrology was held at the California Institute of Technology in Pasadena on February 15, 1947. This was the third meeting of the Section at Pasadena and, as in past meetings, Franklin Thomas was the Program Chairman and made local arrangements. Because of the crowded conditions at Pasadena, it was impossible to hold more than a one-day session. The heavy enrollment in the Institute was such that the meeting could be held only on Saturday at which time the demand for space by students and other activities was not as great as on other days. This may have resulted in reducing the number of those attending. There were, however, about 100 who registered, with an additional number who attended but did not fill out registration cards. There was lively interest in all of the papers.

The morning session, under the chairmanship of M. R. Huberty of the Division of Irrigation and Soils, University of California at Los Angeles, was comprised of four papers, as follows:

(1) M. J. Dowd: Problems of the division of Colorado River water in the lower Basin
(2) C. S. Howard: Quality of water in the upper Colorado River Basin
(3) R. G. Folsom and M. P. O'Brien: The design of current meters
(4) Joseph F. Poland: Salt-water contamination along the shore of the coastal plain in southern California

The first two of these were of a general nature, but dealt with subjects of great interest to hydrologists in southern California. The paper by Folsom and O'Brien was a follow-up of discussions at the meeting of the Section in Sacramento in February, 1946, where the merits of the Hoff and Price current meters were vigorously upheld by users of the two types of instruments. The paper by Poland dealt with a subject which has come to be of great importance especially along the coastal areas in California where the draught on the underground water supply seems to be excessive.

The afternoon session was under the chairmanship of Samuel B. Morris. The session consisted of four papers, as follows:

(5) R. C. Miller and J. A. Putnam: Periodic flow with free surface in porous media
(6) J. D. Isaacs and W. N. Bascom: Elevation of free water in sandy beaches, University of California
(7) Hans Albert Einstein: New developments in the study of sediment transportation
(8) R. T. Knapp: Presentation of problems of harbor protection

The program ended with a visit to the hydraulic laboratory at Azusa, California, which is under the direction of the California Institute of Technology. Here, the experiments on the model harbor of Guam are being conducted.

While the attendance of the meeting was smaller than in the past, considerable interest was shown, and many expressed the opinion that the papers were highly informative and well worth while.

F. J. VEIHMEYER, Chairman, Regional Committee

REGIONAL MEETING, SECTION OF HYDROLOGY, NORTH PACIFIC AREA, APRIL 21-23, 1947

A joint meeting was held in Portland, Oregon, April 21-23, 1947, with the Columbia Basin Water Forecast Committee and the Western Snow Conference. Eighty-four registration cards were signed by representatives from some 14 states and Canada, but attendance at some sessions was greater.

Chairmen of the sessions were: George H. Canfield, District Engineer, U. S. Geological Survey, Portland; G. H. Whyte, Assistant District Chief Engineer, Dominion Water and Power Bureau, Vancouver, Canada, and O. W. Monson, Irrigation Engineer, Montana Agricultural Experiment Station, Bozeman, Montana. George G. West, Corps of Engineers, Portland, is Secretary.

At the banquet on Tuesday evening, April 22, Phil E. Church, Associate Professor of Geography, University of Washington, was toastmaster. John W. Haw, Director, Agricultural Development Department, Northern Pacific Railroad, St. Paul, Minnesota, delivered a timely address on "Future Western Development Depends on Control and Use of Stream Flow."

J. C. STEVENS, Chairman, Regional Committee

MINUTES OF THE FIFTH MEETING OF WASHINGTON GROUP, SECTION OF HYDROLOGY, APRIL 3, 1947

The supper meeting of the Washington Group on April 3, 1947, brought together 42 members and guests to elect officers and to hear Ralph R. Will, Office of the Secretary of Agriculture, speak on the subject, "Present and Future Outlook of Governmental Participation in Natural Resource Development Work."

Officers were nominated and elected for the coming year as follows: Chairman, Carl F. Izzard; Vice-Chairman, Howard Williams; and Secretary, Bernard Frank.

Will's address brought out the growing realization on the part of the public that a greater measure of beneficial use of natural resources as well as more effective protection against deterioration and waste may be achieved through Governmental participation and leadership in the task. He pointed to the growing complexity of conservation efforts and the need for a unified national approach to assure more effective long range utilization of all forms of natural wealth in the public interest. The strong interdependence of all segments of society makes joint effort highly essential. This applies especially, but not exclusively, to the soil and water resources. What forms Federal participation should take is still a debatable issue. Valley authorities and cooperation among existing Federal agencies each has its proponents and opponents. Each has demonstrated advantages and disadvantages. Although a measure of unification has been achieved among existing Federal agencies, the possibilities of closer integration have yet to be developed.

Following questions and discussion, the meeting adjourned at $20^{h}15^{m}$.

BERNARD FRANK, Secretary

Transactions, American Geophysical Union Volume 28, Number 3 June 1947

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, MARCH 10 TO MAY 10, 1947

Elected to Corresponding Membership

Eskola, Prof. Pentti, University of Helsinki, Helsinki, Finland (fg)

Elected to Membership

Andrews, Mr. David A., U. S. Geological Survey, Washington 25, D. C. (fh)
Banta, Mr. Henry E., P. O. Box 6007, Houston 6, Texas (bd)
Barnes, Mr. Chester F., P. O. Box 266, Big Spring, Texas (bdg)
Barrow, Mr. L. T., 3314 Chevy Chase Drive, Houston 6, Texas (abeg)
Bartky, Prof. Walter, University of Chicago, Chicago 37, Ill. (abcdefgh)
Bateman, Dr. Alan M., 91-A Yale Sta., New Haven, Conn. (acfg)
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SPECIAL ANNOUNCEMENTS

New England Meeting of the American Geophysical Union--The Twenty-First Regional Meeting of AGU will be held as a general meeting of the Union, September 17 to 23, 1947, in new England. While plans are still somewhat in a fluid state, it is planned that sessions will be held at Wesleyan University, Middletown, Connecticut; Woods Hole Oceanographic Institution, Massachusetts; and Institute of Geographic Exploration, Harvard University, Cambridge, Massachusetts. In addition inspection trips to some of the many points of scientific interest are being planned. Interested persons should get in touch with members of the General Committee (Richard M. Field, Chairman; Charles F. Brooks; C. O'D. Iselin; H. B. Kinnison; Joe Webb Peoples; and Harlan T. Stetson).

Results of elections--The results of the elections held by mail ballot in March are set forth on pp. 496-497 of this issue of the *Transactions*.

TRANSACTIONS
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APPROXIMATE METHODS FOR DATUM ADJUSTMENTS

John A. O'Keefe

Blanket correction--It is a remarkable fact that when a reasonably rigid survey, A, having a sound first order frame and filled out in the proper manner with second and third order points, is connected to a similar survey, B, the differences in latitude and longitude of common points will be nearly constant as shown in Table 1.

Table 1--Differences in latitude and longitude of common points in two surveys, A and B

Points	Latitude	Longitude
	"	"
1	-6.732	+3.276
2	-6.945	+3.588
3	-6.527	+3.178
4	-6.610	+3.302

This regularity is explained by the fact that the major parts of the differences are caused by different astronomical values being used as origins for the surveys, with their different deflections of the plumb. Evidently, if corrections of -6".7 in latitude and +3".3 in longitude are applied to the B positions, we shall improve the agreement greatly; the remaining residuals will be of the order of ±0".2 or 20 feet. On a map on scale of 1:25,000, this will amount to only about 0.01 inch, which is within the error to be expected from scaling, plotting, paper shrinkage and lack of registration. Therefore, it is satisfactory for most cartographic purposes. On the other hand, it leaves much to be desired geodetically, since no correction has been made for difference of spheroid, nor for difference in azimuth or scale between the two surveys. These differences, imperceptible over a small area, will become extremely serious if the area is large. Moreover, when we consider the requirements of survey, even of the lowest grade, the above mentioned 20 foot cassures are obviously too large.

Use of a complex polynomial--In this Copenhagen prize paper, GAUSS [See "References" at end of paper, 1880] set forth a more refined method for adjusting one survey to another by means of a conformal transformation of x-y coordinates. Gauss proposed that a complex polynomial be used; the coefficients would be determined from the differences in x and y of the two surveys on a few selected points. According to THILO [1926] this method was tested by O. Schreiber, using four points, in an attempt to reduce the triangulation of Mecklenburg to the Prussian system. However, the attempt failed, and the remaining cassures were considerably worse than with a simple blanket correction. An attempt along similar lines was made by the New York Office of the United States Lake Survey. Instead of using only four points, the Lake Survey used all first-order junction points, and derived the best values of a complex polynomial of the second degree by least squares. The results, while better than Schreiber's, were not significantly better than those of Thilo, whose method amounted to the use of terms only up to the first degree. Extension to the third degree was carried out, but without significant improvement. The failure of the method, which was repeatedly attempted, could to some extent be traced. It is well known that if the line integral of a complex function is taken around the boundary of some region, the integral around the boundary must vanish, or the function will cease to the analytic somewhere in the interior. In the case of the Lake Survey problems, it was found that the integral, which could be roughly evaluated by the trapezoidal formula, did not vanish, and that the excess, no matter how distributed, would always lead to cassures of approximately the same amount as those obtained with the first degree polynomial alone. Of course, by using a polynomial with as many terms as there are boundary points, agreement could be secured on these points; elsewhere, however, the polynomial would oscillate so badly that it would be worthless. The development of some mathematical technique sacrificing conformality to some extent for the sake of close agreement on the common points is urgently needed.

Use of a first-degree polynomial--In most cases, an adjustment which will meet the needs of the lower-order surveys can be obtained by the use of a first degree complex polynomial in grid coordinates. Convert the geographical positions of system A to grid coordinates on a certain grid, and those of B to grid coordinates on a grid with the same numerical specifications. The disagreement on the points can now be considered to be due to three fundamental causes, in addition to the inaccuracies of the surveys: (a) The differences in the deflection of the vertical at the datum points;

(b) the differences in azimuth between the systems; and (c) the differences in scale. Corrections for all of these differences are embodied in the first-order complex polynomial. We write:

$$X = m \cos \delta\alpha x + m \sin \delta\alpha y - x_o \quad \ldots\ldots \quad (1)$$

$$Y = m \cos \delta\alpha y - m \sin \delta\alpha x - y_o \quad \ldots\ldots \quad (2)$$

where X is new Easting, Y is new Northing, m is scale ratio (new÷old), $\delta\alpha$ is change in azimuth (new÷old), x is old Easting, and y is old Northing. Equations 1 and 2 are solved by least squares for the values of x_o, y_o, $\delta\alpha$, and m, which will make the sum of the squares of the residuals a minimum. This procedure has proved to be the most useful in practice.

Remarks on the use of grid coordinates--It is important to notice that we cannot in any way map one part of an ellipsoid on another, except in very special cases, without distortion. It is like trying to cut off the end of a football, and use it to patch the side--it cannot be done without stretching. The situation is, in fact, analogous to the mapping of the ellipsoid on the plane. In addition to the translation, rotation, and stretch in the transformation just described, there were also other distortions. Let us imagine that after the least-squares solution is completed, we compute geographical positions from the new grid coordinates (always, of course, by the same set of tables and the same specifications). We have now taken the survey B and remapped it on a new part of the ellipsoid. What sort of distortions have been introduced? Suppose that the projection used for the grid was a conformal projection. The mapping of B onto the plane of the grid was conformal, as was its remapping on the spheroid; hence we have picked up the area B, and, after translation, magnification and rotation, remapped it conformally on the ellipsoid. In the same way, if the intermediate projection had been an equal-area projection, B would have been remapped without change of area (except for that produced by the magnification). If it had been an equidistant projection, distances from the origin, apart from magnification of scale, would have been nearly unchanged in the mapping, though not completely, since the origin would not be at exactly the same point on the ground. If the axis of zero magnification was a certain meridian in the basic projection, the same meridian would be a line of practically no magnification for the mapping from one part of the ellipsoid to another. It should be emphasized that the distortions mentioned here are much smaller than those involved in mapping the ellipsoid on the plane. For many practical purposes, grid coordinates are the raw material and adjusted grid coordinates are the desired end-result; it is therefore important to notice that it is perfectly logical to carry out the adjustment in grid coordinates.

Spheroid-to-spheroid transformations--The problem of going from one spheroid to another is much the same as that of moving an area from one point to another on the same spheroid. It is only necessary that when we convert the area B to grid coordinates, we do so with tables appropriate to the spheroid used for the B triangulation; and when we reconvert to geographic positions, we do so with tables appropriate to the A triangulation. The argument is the same as that for remapping one part of a spheroid on another part of the same spheroid.

Comparison with the methods of the Germans--It is interesting to compare this theory with that used by the Germans. The German work was based on their formulas for the differential changes in the length and azimuth of geodetic line, as a function of the changes in the latitude and longitude of the end-points, and the changes in the a and e of the spheroid. Their first step was to convert the geographic positions of B to the spheroid of A, maintaining the distance and azimuth from the datum point of the survey B, the same on both spheroids. This, of course, is equivalent to mapping the spheroid of B on an azimuthal equidistant projection, and then remapping on A. Second, they set up equations in terms of geographic positions, based on the formulas of HELMERT [1886], which are given here in the notation used in the United States:

$$\delta\phi = - p_1\, \delta\phi_o - p_3\, S{\cdot}K - p_4\, \delta\alpha_o \quad \ldots\ldots \quad (3)$$

$$\delta\lambda = \delta\lambda_o - q_1\, \delta\phi_o - q_3\, S{\cdot}K - q_4\, \delta\alpha_o \quad \ldots\ldots \quad (4)$$

where S is the length of the geodesic P_oP, k is the scale ratio, $\delta\alpha_o$ the change in azimuth; and the p's and q's are coefficients whose values depend on the latitude of both points and the difference of longitude.

Let M = the Earth's radius of curvature in the meridian; N = the Earth's radius of curvature perpendicular to the meridian; and let $l = \lambda - \lambda_o$; and $f = \phi - \phi_o$. Then, following Thilo:

$$\left\{ \begin{array}{c} - p_1 = (M_o/M) \cos l \\ - p_3 S = + p_5 = + f - (l^2/4) \sin (\phi_o + \phi) \sin 1'' \end{array} \right\}$$

$$\left\{\begin{aligned} -p_4 &= (N_o/M_o)\cos\phi_o\sin 1'' \\ -q_1 &= +(M_o/N)\tan\phi\sin 1'' \\ -q_3 S &= +q_5 = +1\cos\phi_o\sec\phi \\ -q_4 &= +p_5\sec\phi\sin 1'' \end{aligned}\right\} \quad (5)$$

These equations yield the changes to be expected in λ and ϕ if the system of geodesics as a whole is rotated, translated, and magnified. The process is almost exactly equivalent to using an azimuthal equidistant projection again and deriving the constants for translation, rotation and stretch in x-y coordinates. The procedure is obviously one requiring skilled computers and considerable time. From a theoretical standpoint it seems actually to be inferior to the use of grid coordinates, since the transformations are not conformal.

Change of projection--In carrying out such unifications as those which have been described, it is frequently necessary to convert grid coordinates from some other grid to the grid adopted for the area. This is fairly easy to do if both grids are conformal since in that case the transformation is of a type known as analytic. Under certain limitations, which do not concern us here, an analytic function can be expressed as a power series in Z.

$$Z = \alpha + \beta z + \gamma z^2 + \delta z^3 + \ldots \quad (6)$$

where

$$\left\{\begin{aligned} \alpha &= \alpha_1 + i\alpha_2 \\ \beta &= \beta_1 + i\beta_2 \\ \gamma &= \gamma_1 + i\gamma_2 \end{aligned}\right\} \quad (7)$$

In order to transform, we must first find the values of $\alpha, \beta, \ldots$ The best way to do this is to find some line along which we can easily express Z in terms of z. For instance, consider a Lambert grid (Z) and a Transverse Mercator grid (z) with the same origin. Suppose first that neither grid has a false easting, and that the Transverse Mercator has no central scale factor or false northing. For the Lambert projection, we know that

$$Y = FN + k_o\,(m + Am^3 + Bm^4 + \ldots) \quad (8)$$

holds, where m is the true meridional distance from the origin, and the values of A, B, ... are given, for example, in JORDAN [1941]. Since $x = X = 0$ for both projections along the central meridian, we can say, just along this line that

$$Z = FN + k_o\,(z + Az^3 + Bz^4 + \ldots) \quad (9)$$

since m is the same as the Transverse Mercator northing. We have thus got Z in terms of z along one line. Now there is a well-known theorem relating to analytic transformations which says that if we can evaluate the power series corresponding to the transformation along any line, that the same power series will work in an extended area around that line. The limitations of this theorem do not concern us here. Thus, comparing equation 6 with 9

$$\left\{\begin{array}{ll} \alpha_1 = FN & \alpha_2 = 0 \\ \beta_1 = k_o & \beta_2 = 0 \\ \gamma_1 = 0 & \gamma_2 = 0 \\ \delta_1 = k_oA & \delta_2 = 0 \end{array}\right\} \quad (10)$$

Now if we introduce a false easting, we can determine α_2 so as to allow for it; and similarly if we introduce a scale factor or a false northing in the Transverse Mercator it can easily be allowed for by changes in the other constants.

To apply such a power series, the Lake Survey found that the most practical method was to treat z as a complex variable, and train the computers in the routine of multiplying complex variables on the machine. Incidentally it should be noted that the Germans have developed a special machine, the Thales GEO, which greatly simplifies the process.

Geographical positions--If the adjustment has been carried out in x-y coordinates, it may be necessary to convert to geographical positions. In addition to the standard methods for such conversions, that is, by tables, it is often convenient, especially for grids of small extent, to resort to power series, such as those given by JORDAN [1941, p. 213] for the Lambert (which he calls the conformal conic projection). Despite its formidable appearance in Jordan's book, this, and the other series which Jordan gives for the Transverse Mercator, Stereographic, and Cassini-Soldner, can, in any given case, be reduced to a simple numerical form which can be mimeographed and distributed. The beauty of this method is that no interpolation is involved. As compared with the standard methods of converting geographical positions to grid coordinates, it is de-skilled, and is particularly suitable when it is necessary to employ untrained computers.

Peace-time applications--It seems likely that some of these techniques may find valuable peace-time applications. For example, it is well known that in certain areas numerous state and local plane coordinate systems meet and overlap. At present, the necessary conversions are often made either by transforming to geographical positions and then to the new grid, or by semi-empirical methods. The formulas for grid-to-grid conversion here described provide a rapid and accurate method for such conversions. Again, it seems possible that some of the methods for datum adjustments which have been described might be employed in adjusting third-order triangulation to the North American Datum of 1927.

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AERIAL NEGATIVES AND PRINTS, THEIR CLASSIFICATION AND PRESERVATION IN THE UNITED STATES

Fred Anderegg

Abstract--A study has been made of the methods of classification and preservation of aerial photographic negatives and prints that are used by various governmental agencies. The general plan of filing is described as well as the availability of prints to users. A more efficient use of the accumulated data can be accomplished by placing all of the records under the care of the National Archives.

Aerial photographs are of great importance in mapping and are thus directly related to all studies of the Earth. Their value in this respect is unanimously recognized and the purely mechanical aspects of aerial photography are also well known to aerial photographers and most cartographers. Fewer persons, however, are acquainted with the equally important problems of classifying and preserving aerial photographic material. In order to determine the present status of these problems in the United States, the writer, at the request of the Chairman of the Commission on Continental and Oceanic Structure, International Union of Geodesy and Geophysics, investigated this country's largest maker and user of aerial photographs, our government. Information was gathered from the Army Air Forces and from the Navy Department, both of which fly their own aerials; from the Hydrographic Office which uses aerials flown by the Navy according to strict specifications; and from the Geological Survey of the Department of Interior and the Soil Conservation Service of the Department of Agriculture both of which acquire their aerial photographs by contract with private concerns. This report deals only with some of the problems confronting the above-mentioned departments. It may also be mentioned that, in order to acquire a clearer world picture, a questionnaire is now being circulated among some of the nations signatory to the IUGG.

Army Air Forces

The Army Air Forces fly and use more aerial photographs than any other department in our government. In order to give the reader an idea of the enormity of the storage problem the following figures are given: At the end of 1944, the Army Air Force alone had over 600,000 cubic feet of film on hand; during the war over twenty million photographs were made each month; the reconnaissance groups over Europe averaged 60 missions per day and used a minimum of 180 cameras; each camera shot an average of 250 negatives and each group made about 45,000 negatives per day; many of these negatives had 50 to 60 prints made from them.

The Army Air Force Photographic Library, as a component of the War Department, is charged with the operation of an integrated aerial photographic pictorial and intelligence photographic file, with laboratory facilities for reproduction purposes to meet the requirements of the Commanding General of the Army Air Forces, render service to all branches and services of the War and Navy Departments and to such government agencies which require these types of photography. This library contains millions of photographs that are in current use. The photographic negatives now on hand total approximately 340,000 rolls of aerial film; 7,000,000 individual cut films, with an anticipated receipt of 300,000 additional rolls; and 1,500,000 pieces of cut film. Thousands of rolls of film have already been received and stored but have not yet been evaluated and processed. The value of this film is recognized but evaluation and processing must await their turn since drastic reduction in personnel was made almost simultaneously with the receipt of the bulk of this unprocessed film from the various war theaters upon cessation of hostilities. Evaluation and processing are continuing, but it will take years for all this film to be reviewed, the record material determined, the non-record material disposed of, and the planned eventual disposition of this film in the National Archives as permanent records.

The present procedure for the preservation of the film includes the reviewing of the material for technical quality, condition, and information. Films are titled and the area definitely determined. This recorded information is registered by the Army Air Force on a punched-card system. By this method aerial photographs of areas can be located quickly within a one degree square. All this film is stored in adequate space under generally ideal conditions required for the preservation of acetate and nitrate film stock.

The print and reference libraries contain approximately 350,000 individual aerial photographic prints; 600,000 aerial mapping photographs; 50,000 photo indices and mosaics; 25,000 plot maps; and 800,000 aerial photographs of the various areas throughout the world in which the armed forces operated during World War II.

The pictorial and documentary files contain approximately 1,200,000 photographic prints. All of this material (unclassified) is available to the public and other government agencies at a nominal charge to cover laboratory and operating costs.

Maintenance of aerial photographic records in the United States

To show photographic coverage, state maps with a scale of 1:500,000 are used and, where necessary, a state map is divided into sections so that, when reduced to 1:1,000,000 each section is 20 inches × 24 inches. These maps are mounted in large books. Each map is covered by a transparent foil overlay. Reference points are precisely marked to permit accurate matching. These maps and overlays show graphically the extent of vertical and trimetrogen aerial photographic coverage flown by the Army Air Force. Appropriate symbols are used in outlining coverage and date.

The map indicates cover flown from 1939 through 1944. The foil overlays indicate additional photography received. There is one overlay for additional 1939-1944 material received since the completion of the map and another overlay for photography taken each year thereafter. There are also special overlays for assembled mosaics.

Areas covered by photography are drawn in outline form on the maps and overlays. Each outline represents area covered by existing photo indices, plot maps, or mosaics. Type of photography is indicated by assigning and I number for photo indices, a TM number for trimetrogon, and an M number for mosaics.

The maps and overlays for vertical and trimetrogon photography show coverage on a small scale and are not suitable for ordering coverage of specific location. Individual exposures can be determined only from a plot map or photo index. A photo index is a copy of photographs at a greatly reduced scale in which the prints are oriented and laid out to show the area covered by each individual picture. In other words this is a very rough mosaic map of the area. Each print of the photo index shows its reference number in the upper right hand corner.

Maintenance of records of areas outside the United States

Mapping and charting photography--Base maps with a scale of 1:6,250,000 on which are outlined areas covered by another set of maps of 1:1,000,000 are mounted in a large book. Complete overlays are used to outline all general mapping and charting photography available. For specific coverage the 1:1,000,000 map is pulled and a foil overlay matched to the map. This shows the specific coverage as to project, roll, and exposure numbers.

Spot photography--Spot photographs representing selected aerial vertical or oblique and ground photographs are filed by one degree squares and then alphabetically by location names within the one degree square. The prints are mounted on 9 inch × 13 1/2 inch cards. Across the top of the file cards are ten main classifications. When the subject of the photograph falls into one or more of these classifications a piece of colored cellulose tape is fastened on the appropriate box. Each type of photography has its distinctive tape color.

An index has been prepared of selected aerial, vertical, oblique, and ground photographs which illustrate various geological and topographic features throughout the world. This index is available for use of educational and other interested organizations.

Pictorial or documentary photographs are filed alphabetically according to subject and location in loose-leaf books for visual inspection. All photographs, for instance, on navigation are filed under N and all instruments used therein are cross-indexed under subject. All photographs of the war are filed according to area, subject, airplanes, bombing, etc.

All selected mapping and charting photographs are considered to be archival records of the United States. All aerial photographic negatives of this type that are no longer of immediate use to the taking organization or to any department of the federal government, are stored in one of two places depending on available storage space. They are either stored with the National Archives or remain in the custody of the Photographic Branch, Air Intelligence Requirements Division, AC/AS-2, Headquarters, Army Air Forces.

United States Navy

This department makes aerial photographs of the United States' coast line and of areas outside this country. The photographic material is classified and filed more or less according to the same system used by the Army Air Forces.

As was the case with the Army Air Forces a tremendous volume of film was shipped to this department upon cessation of hostilities. This coincided with a drastic reduction in personnel so that the present limited staff is overworked. Wooden crates, packed with rolls of film, are piled high in a warehouse with no control whatsoever for humidity and temperature. Since all of this material was processed under war-time conditions a great deal of it is improperly hypoed and washed. It is impossible to tell which films have been processed properly so that it is now necessary to rehypo and rewash all of them. This is being done as fast as possible by the limited personnel. At the same time all of the records accompanying the films are being put in shape, the films are evaluated, properly classified, and indexed. It is estimated that, with the present staff, it will take about ten years to complete this task. In the meantime the film is in wooden crates under far from ideal conditions. At the present rate, part of this important documentary record will deteriorate and be utterly worthless before it can be processed.

Prints are mounted on cards by a method similar to that used by the Army Air Forces. These cards are filed according to: (1) source (outfit, members, etc.), (2) acquisition number (sequence numbers as received), (3) geographic location, and (4) name of place (island, city, etc.). The colored cellulose tape system in the ten classifying boxes across the top of the filing cards is also used. The various colored tapes represent types of photography such as shore, ground photo, vertical, etc.

Hydrographic office--For indexing and filing purposes the world is divided into 25 theaters by the same method employed by the Army Air Forces. Each theater is given a letter designation and is broken down into 4° × 6° (latitude and longitude) numbered zones. Each zone is further broken down into four 2° × 3° lettered parts and each part into six 1° squares.

All aerial photographs, made under Hydrographic Office specifications, are indexed on 1° squares of 1:250,000 by obtaining, or making from existing information, base sheets and overlays on which is shown either vertical, oblique, or tri-metrogon photography. Overlays are made for different types of photography and for different dates and scales of each different type.

This agency compiles topographic data from the aerial photographs but does little mosaic work.

Excellent strips of vertical photographs are taken along coast lines with cross flight photographs normal to the coast at regular intervals. Obliques are also taken from sea toward shore at frequent intervals for views and identification purposes. Two strips of trimetrogon photographs about 15 miles apart are also taken parallel to the coast. With all these cross checks accurate maps can be made.

The film is given an area designation number by the flight crew. The Hydrographic Office assigns consecutive numbers to each roll as it is acquired. The film is then indexed on 1:250,000 and overlays prepared on which appear the number of exposures, scale, date of photography, and any necessary descriptive data. Most of the photography is done by the Navy's Photographic Squadrons.

Photographs are filed by specified theaters and under the same Hydrographic Office number given to the corresponding film. Special files are maintained for photographs on which control or delineation data appear.

Photographs received from other sources are filed under a separate theater file system.

Oblique negatives are generally cut and put into separate containers for filing purposes. Vertical and trimetrogon photographs are retained in rolls. All Hydrographic Office aerial photographic mapping film is stored in adequate temperature and humidity controlled storage vaults.

Other Agencies

United States Geological Survey--All aerial photographs used by this department are acquired by contract. Each contract requires the following to be delivered: (1) all original negatives, (2) two contact prints of each negative, (3) two rough index mosaics for each quadrangle, and (4) a film negative of the index mosaic.

The films are stored in ventilated vaults in Arlington, Virginia, each roll enclosed in a metal container. These vaults have a sprinkler system for fire control but no humidity or temperature controls.

All negatives are marked with the following data: (1) date taken, (2) project designation (by letter), (3) roll number, and (4) negative number. The record of the time of photography and the approximate scale are also recorded on the negatives at the beginning and end of each flight strip. The negatives are left in rolls, each roll being labelled with the project designation and the roll number within that project. The negative rolls are filed by projects and the negative roll record cards are filed in a similar manner.

When the prints are received they are sorted out and filed by quadrangle units (usually by the 15 minute quadrangle although sometimes by the 7 1/2 minute quadrangle). Each print has the accession number stamped on the back. This number shows the year received and the rest of the numbers, which are consecutive, start with one at the beginning of each year. A card record for each quadrangle shows all the pertinent data including flight altitude, camera number, and focal length of the lens used and the designation of all negatives for that quadrangle. Cards are filed alphabetically by quadrangles. On each card appears the geographic coordinates of the southeast corner and the notation 7 1/2 inch or 15 inch quadrangle as the case may be.

Each batch of prints has a wide paper band around it with the quadrangle name written boldly upon it so that it can be seen readily when the file drawer is opened. A photo index is usually supplied in 15 inch quadrangle units, although for larger scale photographs the 7 1/2 inch unit is sometimes used.

The United States Geological Survey has recently published an index map entitled "Aerial Photography of the United States" which shows graphically all aerial photography currently available from the several Federal agencies engaged in mapping and related activities. The last such compilation appeared nearly ten years ago as a publication of the Federal Board of Surveys and Maps. Since that time vast areas of the United States have been photographed from the air, so that today more than three-fourths of the United States is covered by aerial photography. Information on aerial photography from all sources will soon be made available by the Map Information Office, United States Geological Survey.

Soil Convservation Service--Aerial and index negatives are secured for this service through contracts with private concerns. The film is flown according to the following specifications: (1) type and size of camera, (2) focal length of lens, (3) scale, (4) area to be covered, (5) amount of overlap, (6) film alignment, (7) amount of tilt or crab, (8) type of film and paper, and (9) quality of the negatives and prints. The aerial negatives are filed by counties and by projects as well as the symbol assigned. Photo-index sheets for each project are numbered and filed under the project name and also by counties. In order to determine the roll negative required to cover a county it is necessary to refer to the photo-index sheets. If it is required to determine the roll negatives necessary for coverage of an area described by latitude and longitude, the area is plotted on a map (usually a USGS-1:500,000). The county involved is then determined and photo-index sheets covering the county are pulled from the files. The area is plotted on the photo-index sheets and the roll of negatives and exposures required for coverage are determined. The above method is also used where land is described by section, township, and range; metes and bounds description; town names; etc.

Custody of the roll negative is in this Department and all the films are stored in air conditioned vaults.

The standard negative is 1:20,000 for cultivated and timbered areas and 1:31,680 for mountains and range areas. The lens used for the former is an 8 1/4 inch, and the latter a 6 inch focal length.

Photo-index sheets are in the form of mosaics which are prepared by stapling the prints together. Each roll is numbered starting with No. 1 for each project. Each exposure on each roll is numbered, and also starts with No. 1. Each project is given a letter designation. In photographing areas where there are no accurate maps, it is difficult to determine the boundaries of the project from the air. For this, a special camera equipped with a four inch focal length lens is used. This lens gives a coverage of 100°. A trimetrogon camera would do the work as well. From 1936 to 1944, approximately 400,000 square miles have been photographed each year at a scale of 1:20,000 with the 8 1/4 inch lens.

Conclusions

The Army Air Forces and the Navy with its Hydrographic Office use the one degree square method for locating most of their aerial negatives, the United States Geological Survey operates on the basis of quadrangles, and the Soil Conservation Service files their aerial negatives by counties. These differing systems, while each suits the individual needs of that department which uses it, lead not only to various inefficiencies but also to many duplications. For each department to store its own negatives in different locations ranging in condition from ideal to unsatisfactory, from the standpoint of preservation, is both inefficient and unnecessarily expensive. The National Archives should have the proper space and the necessary personnel to acquire all aerial film, record it under one comprehensive filing system, and store it in an easily accessible vault which is under rigid temperature, humidity, and fire control. To date, although it has been the wish of the National Archives to take over this responsibility, and it is their duty by law, they have been unable to do so due to lack of appropriations for a suitable building and adequate personnel.

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GEOLOGICAL EFFECTS ON MICROSEISMS IN THE CARIBBEAN

Leonard M. Murphy

Abstract--The geological influence on the transmission of microseisms in the Caribbean region is extended over new areas. Estimated effective ranges for tracking hurricanes by three types of seismographs are suggested.

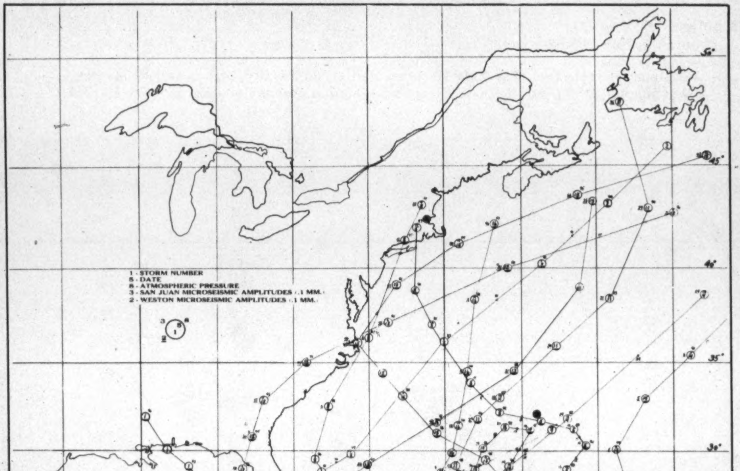
1 - STORM NUMBER
5 - DATE
8 - ATMOSPHERIC PRESSURE
3 - SAN JUAN MICROSEISMIC AMPLITUDES (.1 MM.)
2 - WESTON MICROSEISMIC AMPLITUDES (.1 MM.)
3
5
8
1
2
50°
45°
40°
35°
30°
25°
20°
15°
10°
95°
90°
85°
80°
75°
70°
65°
60°
55°

Fig. 1--Hurricane tracks with microseismic and meteorological data

During the past ten years there has been increasing interest in the origin and nature of microseisms. After the United States Navy became interested in this problem in 1943, a great amount of material, a small part of which is included in this paper, was analyzed at the office of the United States Coast and Geodetic Survey with the result that it was decided by the Navy to investigate microseisms further by means of tripartite stations as an aid in detecting and tracking hurricanes.

Since the Navy project has been in operation, considerable new information has been obtained as to the characteristics, the velocity, and the transmission of these waves. GILMORE, [see "References" at end of paper, 1947] in a recent publication states, "The second major factor that appears to influence the amplitude of the microseisms is the supposed existence of major fault systems in the Caribbean Gulf area. Attention is called to the storms of September and October 1944. Both hurricanes were about the same distance from Guantanamo Bay at a time when their estimated intensities were approximately the same. Yet the storm south and west of the station caused a microseismic amplitude of three times that recorded for the other storm... Data from seismic travel times and the microseismic records are being used to locate fault zones." GUTENBERG, [1947] who has used some of the information gathered by the Coast and Geodetic Survey at its San Juan station, has shown by a hurricane microseismic chart some of the geological influences on microseisms recorded at San Juan, Puerto Rico. He summarizes his results as follows, "Apparently the unusually deep discontinuities between the strongly fractured blocks in the Caribbean prevent most of the energy from spreading from one geological block to the next."

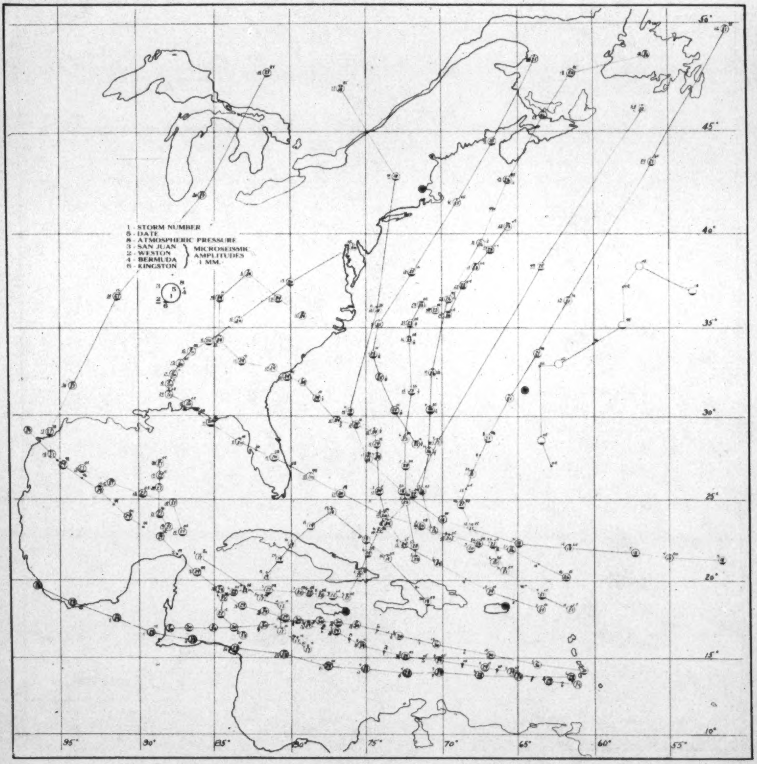

Fig. 2--Hurricane tracks with microseismic and meteorological data

Inasmuch as the number of available storms during the recent years of most intensive study in the Caribbean region was very limited and there were so many severe hurricanes since 1932, it was decided to investigate the possible correlation of microseismic amplitudes at four important stations in the Caribbean region and along the Atlantic Coast with known hurricanes to secure additional information on the geological influence on the transmission of microseisms, and also the maximum distance at which the hurricanes may be detected and tracked by ordinary teleseismic seismographs.

Hurricanes from 1932 through 1945 were examined in order to obtain adequate readings at the teleseismic stations for a maximum number of storms. Very often, after obtaining good correlation between microseismic amplitudes and one station, the next station along the path was out of operation and therefore the relationship is only partially illustrated. Because of this, 42 hurricanes were finally picked for this study. Seismograms from Weston, Massachusetts (Benioff, Z), Bermuda (Milne-Shaw, NE), San Juan (Wenner, EW), and Kingston, Jamaica (Milne-Shaw, EW), were scaled and plotted on Figures 1, 2, and 3, along with the paths of the hurricanes. The path is indicated by the storm number in the center of the circle and the time of Greenwich day by a shaded base for 0^h, a dot for 06^h, a plain circle for 12^h, and another dot for 18^h. The trace amplitudes from all stations were plotted about these circles and dots and may be identified by the key on each figure. The atmospheric pressure (mb) is also on the figures, usually in the first quadrant.

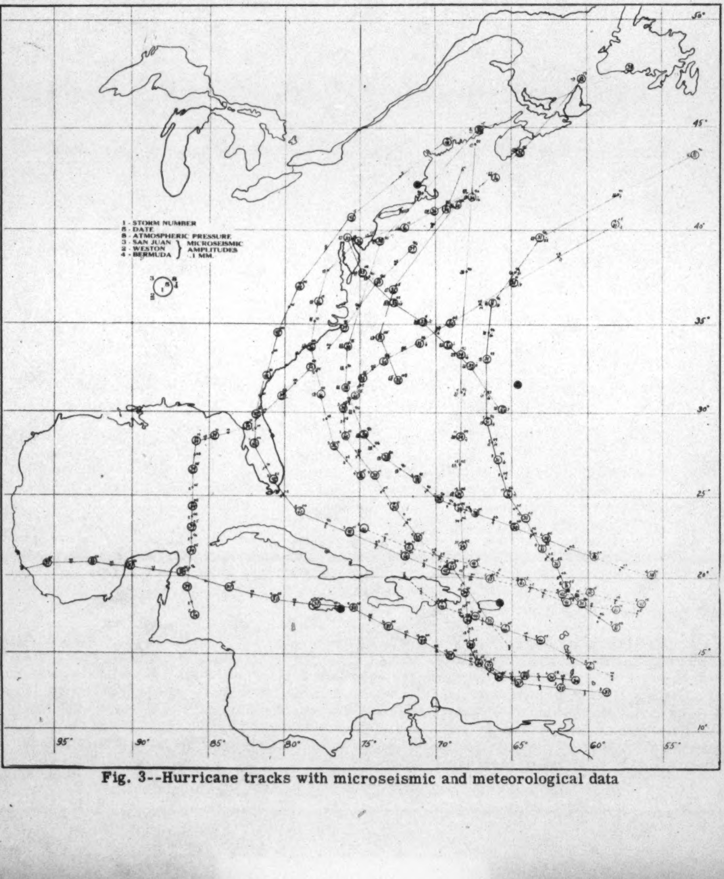

Fig. 3--Hurricane tracks with microseismic and meteorological data

As may be observed from the first three figures, the details become very complex and are presented here only as a concise source for all of the information required for this analysis. In order to illustrate the geological influence upon microseismic transmission the essential data have been abstracted on Figures 4 and 5.

On Figure 4 are plotted all of the storms well recorded at San Juan and Kingston. The track numbers are identical with those found on the previous figures and also the microseismic amplitudes which indicate the most significant increase and decrease in the values or the effective range during the course of the storm are recorded as exponents at the beginning and end of each storm respectively. In the case of a few storms originating southeast of Puerto Rico the initial changes in amplitude from normal are indicated and not the most significant increment.

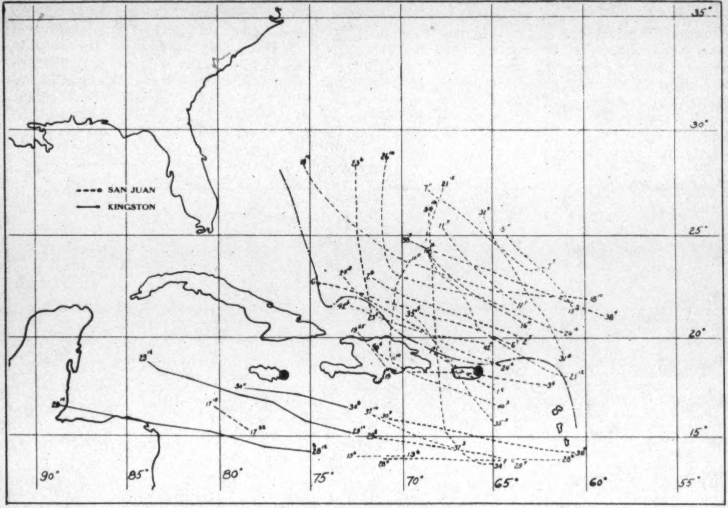

Fig. 4--Hurricane tracks

If all of the storms are considered which pass over deep water north of San Juan, it is observed that there are well defined microseisms for an approximate range of 650 miles with only a few questionable exceptions. It is believed that this range is caused essentially by two conditions; namely, the intensity of the hurricane, and the sensitivity of the seismograph; it is not influenced by any geological discontinuities.

A demarcation line (dash and dot) was drawn on Figure 4, indicating deep water on the north and shallow water on the south, which illustrates very remarkably that practically no microseisms of significant value are recorded over the shallow water. For the storms east and west of Puerto Rico and also crossing the island, the amplitudes are very small although there is no doubt that they are not associated with the hurricanes.

South of Puerto Rico the most significant geological influence is indicated by the storms which originate near the Windward Islands and travel in a westerly direction. As the storms travel north of the Curaçao ridge where there is deep water the microseisms are well defined but as they cross the Beata ridge, south of the peninsula in southwest Dominican Republic, although the storm intensities have not diminished, the recorded amplitudes at San Juan have returned practically to normal. Inasmuch as this position is only 400 miles from San Juan, it certainly is within the range of microseisms to be well recorded at this station as is illustrated by the storms north of Puerto Rico which have an effective range of 650 miles.

For some of these westerly hurricanes it was fortunate to have available a few Kingston, Jamaica seismograms to illustrate this geological effect on the microseisms for storms on the east and west side of the Beata ridge. Although there was considerable transportation delay in receiving these data after John A. Blatchford of Kingston made them available last summer, it was decided that these readings were of sufficient value to delay release of this paper from mid-summer 1946, to the present time. From Figure 4 it is observed that there is no change in the normal Kingston microseisms until the westerly directed hurricanes have crossed the Beata ridge, although the storms have considerable intensity and are within the probable range of the Milne-Shaw seismograph. As the storms then pass over the deep water south of central Cuba, there are always well-recorded microseisms at Kingston. Because of the limited results available it is difficult to estimate an effective range for this station although 400 miles appears to be a reasonable value.

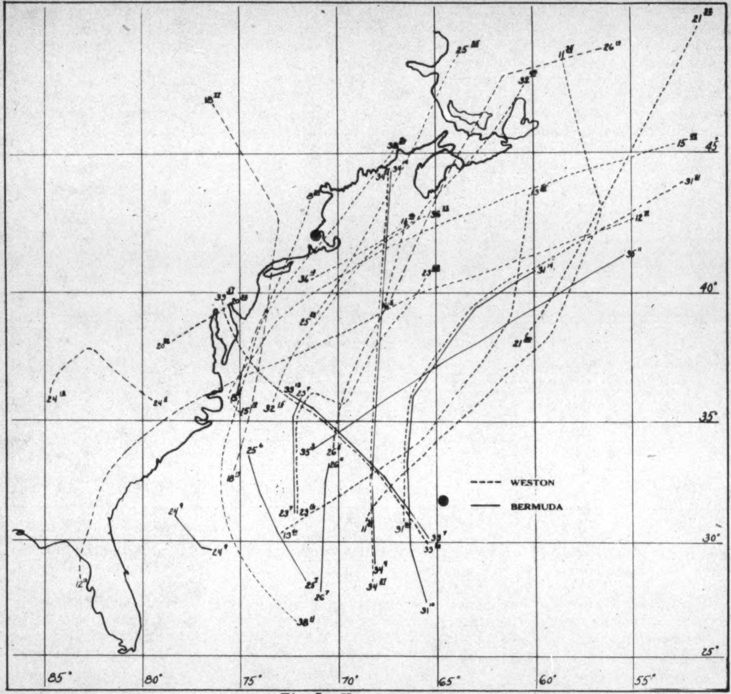

Fig. 5--Hurricane tracks

As the hurricanes travel north of the Caribbean region and along the east coast of the United States, there appears to be very little geological influence on the transmission of the microseisms to Bermuda and Weston. In the analysis of Figure 5, an attempt is made to illustrate the effective range of the microseisms recorded on the Weston Benioff seismograph, although the hurricanes in many cases are diminishing in intensity and the centers are being disintegrated over very large areas. Hurricanes that are over deep water are definitely indicated to the south at a distance of approximately 1200 miles, and to the northeast where the storm is usually disintegrating at a distance of 1900 miles. It should also be noted that the amplitudes indicated are of much larger values and therefore are easier to identify and to associate with hurricanes. This is also true with extra-tropical storms along the Great Lakes, the St. Lawrence Valley, and the North Atlantic Ocean.

The microseisms recorded at Bermuda are also plotted on Figure 5 for the available records since 1940. Using the same procedure followed at the previous stations the storms are seldom recorded more than 220 to 250 miles south of the island. Very often they have already passed the island before any appreciable change has been observed in the amplitudes. On Figure 5 there are indications that the storms may be recorded at least for 550 miles beyond the island, although there is some question as to the limit to which microseisms at this particular station may be associated with the hurricanes.

In conclusion it may be stated that the reading of these microseisms on old seismograms has definitely extended some of the results obtained in current microseismic research which has been handicapped by the extremely limited number of hurricanes during the 1943-1946 seasons. Also the results especially at Kingston and San Juan definitely establish the geological influence on the transmission of microseisms through geological discontinuities in the Caribbean region. An estimate of the effective range for tracking hurricanes over deep water is indicated for three types of seismographs; namely, Benioff vertical about 1200 to 1900 miles, the Wenner horizontal about 650 miles, and the Milne-Shaw horizontal about 220 to 400 miles and with some doubt to 550 miles. It is also evident that sensitive seismographs give considerably more effective ranges for recording microseisms which may be used as aids for detecting and tracking hurricanes and for supplying more adequate information for research on the nature of these waves.

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NON-AMBIGUOUS SIXTEEN-POINT CHART RECORDING OF WIND DIRECTION FROM A STANDARD EIGHT-POINT CONTACTING WIND VANE

Ronald L. Ives

Abstract--This paper discusses methods of obtaining a continuous chart record of wind direction to 16 points, from a standard eight-point contacting wind vane, without either position ambiguities or "sweeps."

Introduction--Methods of obtaining continuous chart records of wind direction to eight points, from a standard eight-point contacting wind vane, have been outlined by IVES [see "References" at end of paper, 1946]. Similar recordings to 16 points, but with a 180-degree position ambiguity in some positions, have been secured by GRINNELL [1945]. Numerous workable alternatives to both methods are possible, several being outlined by MIDDLETON [1942].

Various attempts to secure nonambiguous 16-point continuous wind-direction records from a standard eight-point contacting vane have been made, one of the more successful being the use of an interpolating contactor [IVES, 1946], controlled by the wind vane, and controlling a tapped series resistor in the recorder-battery circuit. This and related recorder systems, although workable, are mechanically and electrically unwieldy, and have a poor response at that point where a directional change of $\pi/8$ radians causes the pen to sweep the chart; that is, to traverse its entire width. Constructional cost is also great; such an installation requires 16 three-pole relays, 16 odd-valued precision resistors, and numerous auxiliaries.

Folded scales--Elimination of sweep between a pair of directional points requires either that the recording chart be circular and the recorder pen be free to rotate continuously about its axis, a procedure that is not practicable with existing equipment, or that the direction scale be folded back upon itself.

Use of a folded scale, while eliminating sweep, introduces 180-degree ambiguity at all points. This ambiguity may be eliminated by use of an auxiliary indicator, as in Figure 1, to show when the direction indicated exceeds 180 degrees or lies in any other predetermined semicircle. The use of a secondary indicator (chronograph pen) eliminates 180-degree direction ambiguity.

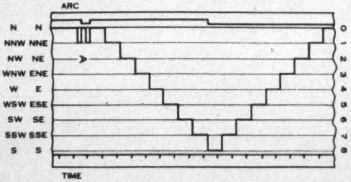

Fig. 1--Folded direction scale, to eliminate sweep

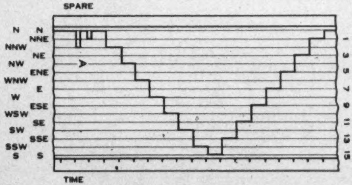

Fig. 2--Folded and interfingered scale, needing no auxiliary indicator

By modifying the scale-division system slightly, a folded and interfingered scale, needing no auxiliary indicator, is produced. One form of this is shown in Figure 2. Numerous workable alternative arrangements, using the same general principles, are possible. Interfingering is possible only when each direction is represented by a definite position, and separated from the next position by a finite interval. Interfingering cannot be used successfully with continuously-variable resistive indicating vanes.

Interpolating bridge--Largely as a result of the work of S. W. GRINNELL [1945], the problem of obtaining an intermediate direction indication when two adjacent contacts on the wind vane are bridged (closed simultaneously) has been solved. This is made possible by use of an interpolating bridge, shown diagrammatically in Figure 3. In Figure 3, E is the voltage indicated on a "drainless" voltmeter, having an external multiplier Z. Supply voltage is Es. Resistors X_1 and X_2 are equal. All resistors marked Y are equal. In consequence, so far as potential alone is concerned, point A is equivalent to the mid-point of X_1; and point B to that of X_2. When the voltmeter is connected to point A alone, its indication, assuming no drain, is shown by

$$E = [(X_1/2)/(X_1 + X_2)]Es = Es/4 \text{ (when } x_1 = x_2) \ldots\ldots\ldots\ldots (1)$$

and, when connected to B alone, indicated voltage is

$$E = [(X_1 + X_2/2)/(X_1 + X_2)]Es = Es/4 \text{ (when } x_1 = x_2) \ldots\ldots\ldots (2)$$

When the voltmeter is connected to both A and B, which occurs when two adjacent vane contacts are bridged, indicated voltage is

$$E = Es/2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

again assuming no current through the meter circuit.

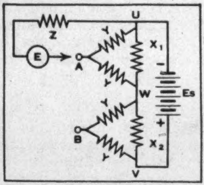

Fig. 3--Diagram of simplified interpolating bridge

Numerous extensions and modifications of this general principle are possible to cover a variety of conditions and recorder needs.

Azimuth indicator circuit--The azimuth indicator circuit operates to show in the recorder chart, either by position of the edge pen on a folded scale or by that of the direction indications on a folded and interfingered scale, whether the wind source, as shown by the position of the vane, is between 0° and 180°, or between 180° and 360°. Any other diametric division of the circle may be used.

Wiring diagram of one form of the azimuth indicating circuit is shown in Figure 4. This is actually a pair of discrete and identical electrical circuits, sharing a single magnetic system and contacting arrangement. All components marked A in this Figure are parts of one circuit, controlled by the north arc of contacts; those marked B are controlled by the south contact arc.

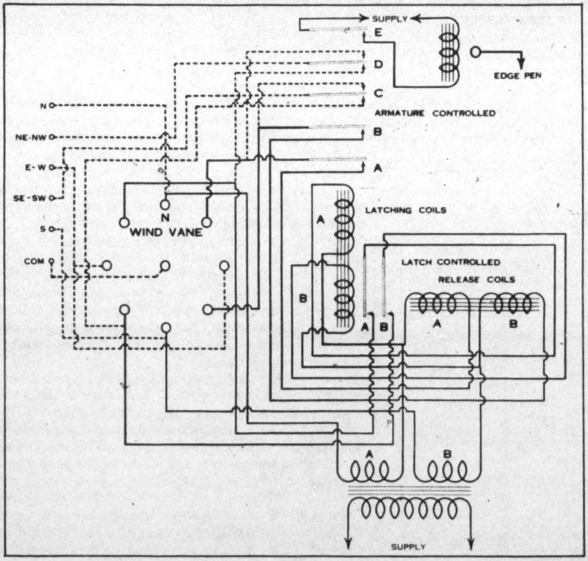

Fig. 4--Circuit of azimuth indicator; azimuth components are shown in solid lines, direction components by dashed lines

The important component of this arrangement (see Fig. 4) is the transfer relay, which is an electrical release latching-type relay with two identical coils on both the latching and release cores, and with a pair of contacts on and controlled by the latch armature. Although this portion of the circuit can be operated on either AC or DC, and may, when used alone, operate from a single power supply, AC operation from separate secondaries is here shown. This is necessary to prevent circuit conflicts when the other components comprising the direction-indicator circuit and its auxiliaries are connected.

In normal operation, when the wind-vane contactor is in the east position, the armature controlled contacts are in "up" position and the latch controlled contacts are closed. As the wind vane swings counterclockwise across north, the northwest and north are bridged, at least momentarily. This energizes the A latching circuit, current flowing from the left end of the A transformer secondary (see Fig. 4) to the north vane contact, thence through the vane contactor to the northwest contact, through latch-controlled contacts A (which are closed), and through the A latching coil to the right end of the A transformer winding. This energizes the latching magnet, which pulls down the armature, placing all the armature-controlled contactors in "down" position. When this occurs, the latch snaps over immediately, locking the armature in "down" position, and opening the latch-controlled contacts, so that no more current flows in the latching circuit, regardless of how long the contact is maintained. Operations controlled by the other contacts of the relay (armature-controlled C, D, E, etc.) are automatically performed at the same time.

An identical series of operations takes place in the B circuit when the vane contactor rotates clockwise from east position to and beyond southwest position. When the vane contactor rotates clockwise from west position, it bridges the north and northeast contacts, at least momentarily. When this occurs, the A release circuit is actuated. Current flows from the left end of the A transformer secondary to the north contact; thence through the vane contactor to the northeast contact; then through the armature-controlled contacts A, which are closed, to release coil A; and thence to the right end of the A secondary of the transformer. This energizes the release magnet, pulling in the latch, which then releases the main armature. This armature rises, placing all armature-controlled contacts in "up" position. Opening of armature-controlled A contacts opens the A release circuit, so that no more current flows in the circuit regardless of how long the contact is maintained. Operations controlled by the other contacts of the relay are automatically performed at the same time.

An identical series of operations takes place in the B circuit when the vane contactor travels counterclockwise from west position to and beyond southeast position.

Indicator circuits--Indicator circuits for both recording systems are extensions of the interpolating bridge, previously described (see Fig. 3), and substantially identical circuits, outlined in Figure 5, are used in both. It will be noted in Figure 5 that the first resistor is replaced by a pair of choke coils to keep AC out of the meter.

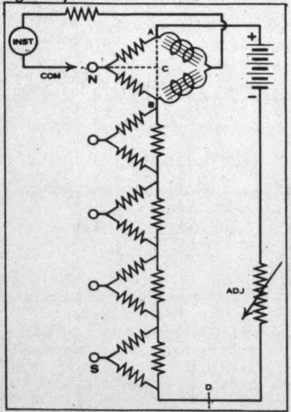

Fig. 5--Interpolating bridge used in indicator circuits

If the bridge of Figure 5 is connected directly to the azimuth indicator of Figure 4, the recorder circuit for use of the folded system of recording is complete, each resistive point serving two vane positions except for the north and south points which are common to both semicircles. To prevent circuit conflicts, the second and fourth resistive deltas of the bridge are connected to only one contact at a time (contacts C and D in Figure 4). If this were not done, bridging of any pair of azimuth control contacts would energize both azimuth circuits, producing undesired electrical results. This circuit conflict may also be eliminated by use of two choke coils, which isolate critical pairs of contacts with respect to AC but connect them together with respect to low-current DC. This is shown in Figure 6. These choke coils may be used in place of the switching arrangement (contacts C and D) in Figure 4, provided resistive adjustments are made in the indicator circuit.

It is usually necessary, when chokes are used, to insert compensating resistors in the indicator circuit. These compensators are so complex that the use of choke-coil circuit isolation in place of switching arrangements is usually inadvisable. The edge pen of Figure 4 indicates the

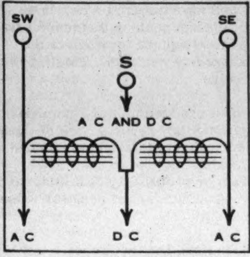

Fig. 6--Use of choke coils to prevent circuit conflicts

semicircle as is shown in Figure 1. Reverse arrangement may be used if desired. When folded and interfingered recording is desired, as in Figure 2, the edge-pen circuit of Figure 4 is omitted, and subsidiary resistors are inserted in the bridge by additional relay contacts (not shown) on the azimuth control (Figure 4).

In the 0°-to-180° semicircle, a resistive T is inserted in the north "diamond" of the resistive bridge, so that when the north and northeast contacts are connected together by the vane contactor the indicated position is no longer midway but is one third of the distance between north and northeast. This T is composed of resistors AC and CB of equal values and CN of relatively larger value.

In the 180°-to-360° semicircle, the resistive T is removed from the north "diamond," and a resistive change introduced at D (see Fig. 5) by relay contacts to bring all points except south to the desired value. South position, in this semicircle, is determined by the stop pin of the instrument. This same effect can be produced by use of a resistive T at this point.

Circuit constants--Although a resistive recorder of either type described can be constructed and made to work with a wide variety of instruments and resistive values, the practical-component range is rather narrowly confined by the constants of equipment available and the current demands of the circuits.

The azimuth control circuit is best constructed for operation on approximately six volts AC, using commercial relay coils having a nominal two-watt rating. This permits the use of standard components of commercial relays, while keeping the circuit potential at a minimum.

When a one milliampere recorder is used in this circuit, with a six-volt battery, current drain through the Y elements of the resistive bridge (see Fig. 3) never exceeds one ma and the Z resistor in the instrument circuit approximates 5000 ohms. If the Y resistors are valued at 250 ohms, and the X resistors at 50 ohms, the resistive bridge can be constructed with stock resistors, and will have an accuracy of close to 99 per cent. Minor resistive adjustments to increase the accuracy can be made by "cut and try" methods in one afternoon.

Computation of resistor values for either a high-drain recording instrument, or a low-overall-drain bridge is possible by use of conventional network computations which become very involved in this application. In many instances a good electrical technician can determine the necessary values within the desired limits of accuracy more rapidly by trial and error than a good mathematician can compute them. Use of odd-valued resistors necessary in special systems also increases construction cost greatly and may extend the service interruption caused by failure of a single component from a few minutes to a few months.

Operating data--Experience with several experimental recorders of this type built with "war" components and used in a desert location indicates that the resistive portion lasts indefinitely and needs no maintenace, provided stable components are used ("one-per cent wire-wound" resistors, rather than carbon resistors).

In the desert the azimuth relay requires contact service after each 250 hours of use. Contact life between service shutdowns may be extended to about a month by use of a dust cover together with the insertion of suitable spark absorbers which must be carefully designed to prevent introduction of inductive kicks into the meter circuit. Checking of the operation of the azimuth relay each time the recorder chart is changed, and correction of any noted deficiency, seems desirable as a routine trouble-prevention measure.

Alternative circuits--Several attempts to develop an "all DC" recorder of the folded and interfingered type were made, and one working model was developed. This, employing cascaded time-delay circuits to produce the requisite circuit isolation, was found too complicated for field use, not well suited for laboratory use, and too demanding of maintenance to have any real value as a research instrument. For field use an AC-DC recorder as previously described works well from a standard inverter, costs less, and has fewer components than the experimental "all DC" type, and does not need a skilled maintainer in constant attendance.

Attempts to produce a resistive bridge for use with the folded and interfingered type of recording without an azimuth circuit have to date been unsuccessful, although such an instrument is not only needed but is at least theoretically possible. By use of an interfingered interpolating bridge, the desired type of recording is obtained with an error of about five per cent. This is just enough deviation to make chart interpretation unworkably difficult.

Conclusions--Both of the recording systems described, even when used with "war" components in an unfavorable environment, perform as desired, with a good dependability record. Use of these instruments in several types of research seems desirable. Additional efforts to produce a folded and interfingered type record by use of a bridge circuit alone are needed because an instrument of this type is capable of functioning for long periods without attention or probability of failure, and can be constructed to operate for long periods with a small battery. Computation of resistor values by use of a "brass brain" will probably be necessary.

Acknowledgments--The writer is indebted to S. W. Grinnell of Stanford University for many helpful discussions of recording problems; to R. A. Arnberg, CWS, for field assistance; and to Evelyn L. Kroona, WAC, for office assistance.

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ON THE KINEMATICS AND THERMODYNAMICS OF GENERAL CIRCULATION OF THE ATMOSPHERE IN THE HIGHER LATITUDES

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Abstract--The weather pattern associated with waves in the Westerlies of the higher latitudes indicates ascending motion near the troughs and descending motion near the ridges, so that the trajectory of each air parcel that flows eastward through the waves has the three-dimensional form of a left-handed helix. Non-adiabatic cooling and heating of the air, as it flows poleward and equatorward along its helical path, causes the air to lose heat when its pressure is low and to gain heat when its pressure is high, making the circulation work-producing. It is shown that the kinetic energy thus generated is of the same order of magnitude as the dissipation of the kinetic energy by internal and surface friction, thus causing the Westerlies to be maintained in a steady state.

Introduction--Synoptic charts of the middle and upper troposphere for the Earth show an instantaneous horizontal velocity distribution similar to that given schematically by the streamlines in Figure 1. In the lower latitudes the synoptic pattern shows large anticyclonic circulations. In the higher latitudes circumpolar Westerlies are found. The horizontal streamlines of the Westerlies are wave-shaped, with the maximum wave amplitudes near the center of the current. Along the trough and ridge lines of some of the westerly waves, small closed streamlines are found, but the volume of air which participates in these closed circulations is very small. The size and strength of the Westerlies, relative to the lower latitude anticyclones, changes with the season of the year; the Westerlies are broad and strong in winter, narrow and weak in summer.

From one day's map to the next, the lower latitude anticyclones in general change their positions very little. The waves in the Westerlies of the higher latitudes, on the other hand, are in a steady procession eastward, the trough and ridge lines of the waves turning slowly about the poles. The air itself, in the Westerlies of the middle and upper troposphere, flows eastward through the waves with a greater speed. The air alternately overtakes a trough line and a ridge line, causing the horizontal projection of the path of each air parcel to be itself wave-shaped.

The structure and thermodynamics of the lower latitude anticyclones were described, some years ago, in the cell theory of BJERKNES [see "References" at end of paper, 1935]. It was shown that the planes of the orbits of the air parcels in the anticyclones are inclined upwards toward the west, so that the paths of the parcels embrace a positive number of solenoids, making the circulation work-producing.

It will be shown here that an analogous circulation exists in the Westerlies of the middle and upper troposphere, with the inclined elliptical orbits of the air parcels in the lower latitude anticyclones replaced by helical orbits in the Westerlies.

Kinematics of the westerly circulation--The horizontal components of the motion in a wave in the upper Westerlies, as described above, are known through pilot-balloon observations. The vertical components of the motion can be inferred, at least qualitatively, by indirect aerology. Experience with the weather indicates that the maximum middle and high cloudiness and the heaviest precipitation normally occur in advance and close to the trough line of the westerly wave, whereas, near the ridge line, the skies are clear, with a subsidence inversion often present. The air, whose cooling produces the cloudiness and precipitation, must then be rising where it overtakes the trough line and subsiding where it overtakes the ridge line of the wave. With vertical motion deduced in this fashion, the instantaneous field of vertical velocity in a westerly wave (in the Northern Hemisphere) is given schematically by the broken lines in Figure 2. In three dimensions, each streamline is a left-handed helix, directed from west to east, as in Figure 3.

Because the air moves eastward faster than the waves, the three-dimensional trajectory of each air parcel in the middle and upper Westerlies must also have the form of a left-handed helix. The resulting circulation is shown schematically in the upper part of Figure 4. The lower part of

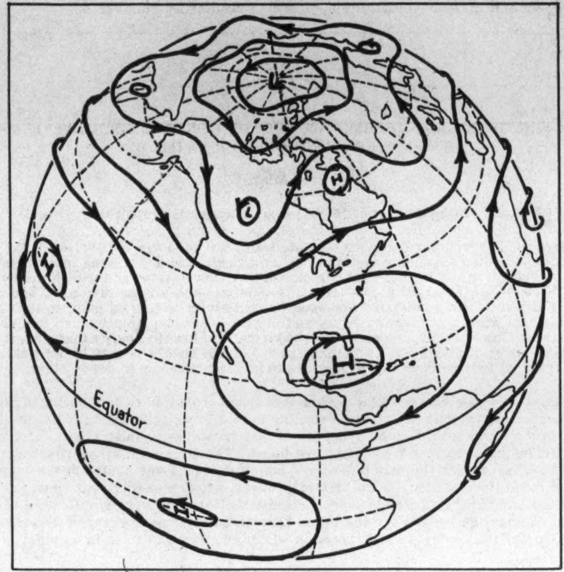

Fig. 1--The horizontal field of motion, at a given instant, in the middle and upper troposphere

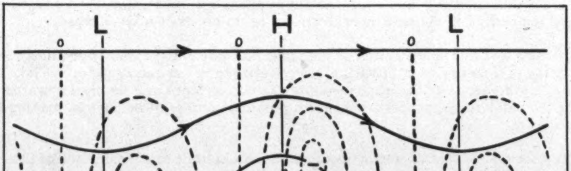

Figure 2--The field of motion in a westerly wave; the solid lines are horizontal streamlines, the broken lines are isopleths of positive and negative vertical velocity

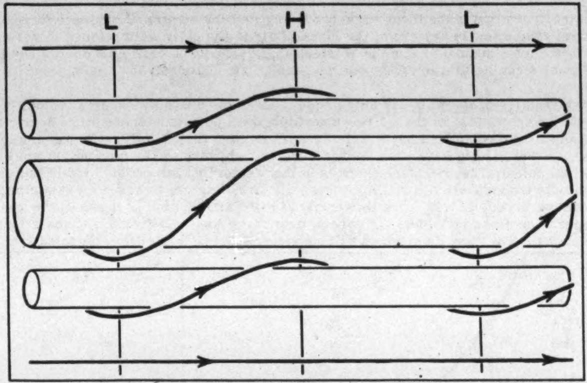

Fig. 3--Three-dimensional streamlines of the flow shown in Figure 2

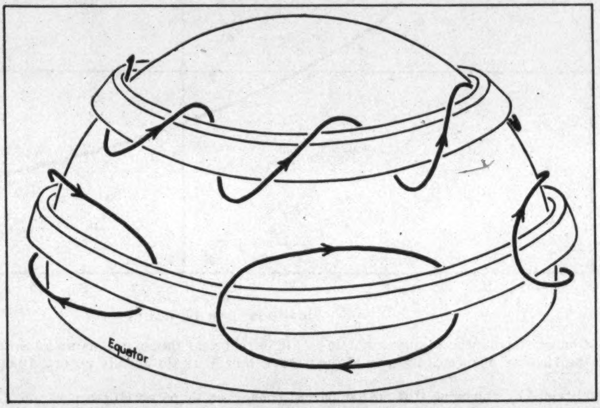

Fig. 4--Schematic representation of the general circulation of the atmosphere, showing air trajectories in high and low latitudes

Figure 4 shows the circulation in the lower latitude anticyclones, as described by BJERKNES.

Figure 4 shows the path of only a single air parcel of the Westerlies, for reason of convenience in drawing. One can also think of the westerly helical circulation in terms of the whole vertical column of air in which the individual air parcel finds itself. This column, as it moves eastward, will swing north and south along a wave-shaped course. The bottom of the column will move along the Earth's surface, the motion at the bottom being horizontal where the Earth is flat. At some high elevation in the column, say at the level of the tropopause, the motion can again be taken to be horizontal. But between these two levels all the air parcels in the column move vertically upward as the column moves eastward through the region just preceding the trough line of the horizontal wave, and then downward in the region just preceding the ridge, with the level of maximum vertical displacement within the moving column constituting the level of non-divergence.

Centered over and near the poles, shallow high pressure areas are found, with anticyclonic circulations around the centers of the highs. It seems reasonable to expect that these circulations also have structures that make them work-producing, but the empirical evidence for determining this is not yet available. In any event, the mass of air in the polar anticyclones is very small compared to the total mass of air in the Westerlies, so that for a working model of the first approximation, Figure 4 can be said to represent the general circulation of the atmosphere.

Thermodynamics of the westerly circulation--Given the above kinematical model of westerly flow, if it can be shown that as the air flows northward its potential temperature decreases and as it flows southward its potential temperature increases, then the air will be losing heat when its pressure is low and gaining heat when its pressure is high, making the circulation work-producing. That the actual potential temperature changes in the Westerlies are of this kind is indicated, for the lower middle troposphere at least, by Figure 5. This diagram is based on data computed at the AAF Weather Station at New York University [ANONYMOUS, 1945]. It shows the change in potential temperature on an individual air parcel, near three km, as a function of the change of latitude of the parcel. This was determined by comparing vertical velocities computed kinematically with those obtained by assuming that the air parcel conserves its potential temperature. In order to follow the individual air parcels, only cases were used in which no condensation took place along the path of the parcels. The dispersion of points on either side of the curve is to be expected, because the non-adiabatic temperature change on any individual air parcel depends on such factors as type of ground cover, surface temperature gradient, high cloudiness, humidity of the air, season of year, etc., in addition to the latitude change of the parcel. But the curve of best fit, as given, may be regarded as roughly representing the normal condition in the Westerlies. It passes below the origin, showing that with no south-north motion there is a residual non-adiabatic cooling. From this feature, the curve can be interpreted as representing two effects, one the cooling of the air with northward flow and heating of the air with southward flow, the other the residual cooling independent of the south-north motion. For use in our model, this residual cooling is assumed to be that cooling of the air by long-wave radiation and the turbulent transfer of heat downward which balances the heat added to the air by condensation.

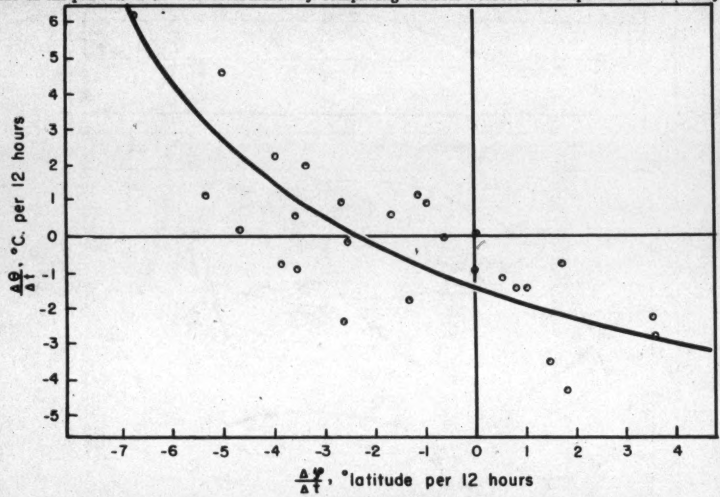

Fig. 5--Change in potential temperature on an air parcel near three km, shown as a function of the 12-hour change of latitude of the parcel [New York University report, 1945]

Examination of horizontal trajectories, as found by synoptic analysis of a number of cases, indicates that in a typical middle troposphere wave the period of the trajectory is about six days, 40 mph is the average horizontal wind speed, and 20° latitude is the horizontal amplitude of the trajectory. An air parcel following such a path experiences about ± 3°.3 change of latitude per 12 hours as its mean rate of change of latitude between trough and ridge lines.

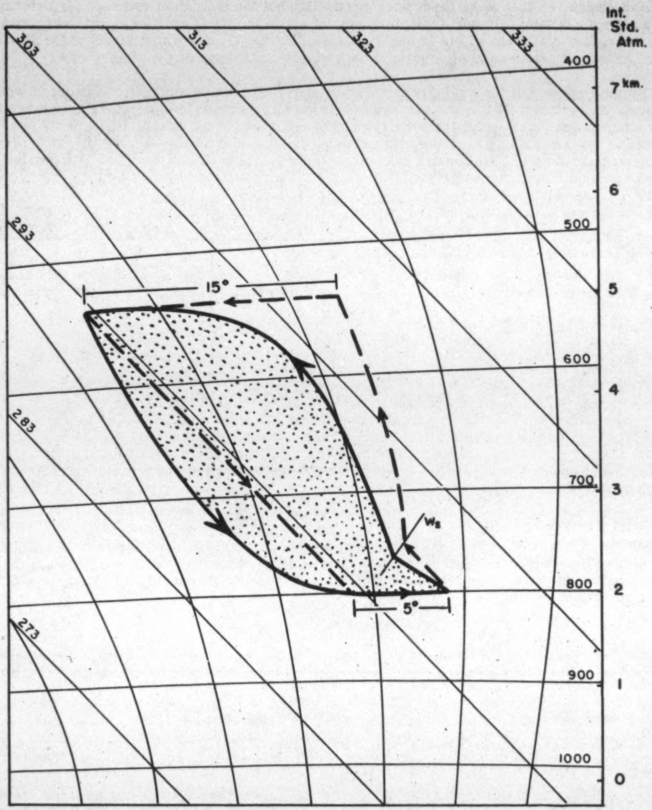

Fig. 6--Image curve of a symmetrical westerly helical trajectory in the tephigram

From Figure 5, +3.°3 latitude change per 12 hours gives a total potential temperature change of -15°C in three days; and -3.°3 latitude change per 12 hours gives +5°C temperature change in three days: so that the total residual cooling over the six-day period is -10°C. In order for this residual cooling to be compensated by latent heat of condensation, a representative air parcel, with initial pressure of 800 mb, potential temperature 297° A and relative humidity 70 per cent must be displaced to a pressure of 540 mb, or about three km vertically. (A vertical displacement of ± three km in three days gives an average vertical velocity of ± 1.2 cm per second.) The broken line in Figure 6 shows the thermodynamic cycle taken in separate steps, the parcel first being lifted three km vertically and cooling adiabatically at the unsaturated and saturated rates, then losing heat non-adiabatically as it flows northward for three days at constant pressure, descending adiabatically to 800 mb, and then gaining heat non-adiabatically as it flows southward for three days at constant pressure again. We have assumed that the data of Figure 5, which shows the change of potential temperature of a parcel as a function of its change of latitude, are applicable as a first approximation to saturated as well as unsaturated air.

The heavy continuous line in Figure 6 shows the thermodynamic cycle as a continuous process. Near the trough line, where the air parcel is ascending, the non-adiabatic cooling causes the air to cool at a rate greater than that of the unsaturated and saturated adiabatics. Near the ridge line, where the parcel is descending but where the north to south motion is still small, the residual non-adiabatic cooling causes the air to heat at a rate smaller than that of the unsaturated adiabatic. The area enclosed by the path of the air parcel in the tephigram represents a conversion from heat to work of 850 kj per ton per six days, or 1.6×10^{-3}kj ton^{-1} sec^{-1}. Because at the end of each cycle, in our model, the air parcel returns to its original temperature and elevation, neither the internal nor potential energy of the system is changed, so that all of the heat energy is converted into kinetic energy. Each parcel in the air column above and below the parcel just described will show a kinetic energy conversion of this kind, the rate in each case depending on the vertical displacement and the time it takes the parcel to complete a cycle. In order that the cycles can be gone through over and over again, it is assumed that whatever moisture is lost to each parcel by precipitation during its ascent is returned to it, along the remainder of its path, by surface evaporation and the turbulent transfer of the moisture upward.

The total kinetic energy production, Δ_K, in column of air of unit cross section area and extending from the ground to ten km, can be found by performing the integration in the equation,

$$\Delta_K = \int_0^{10\text{km}} K\rho dz$$

where K is the rate of energy production per unit mass, ρ is the density, and z is the elevation.

In the above model, K depends on the vertical displacement and will be at a maximum near the level of non-divergence. Let us assume that the height of this maximum is five km and that K then decreases linearly to zero at the ground and to zero at ten km, roughly the height of the tropopause. Taking the value of 1.6×10^{-3} kj ton $^{-1}$ sec $^{-1}$, as found above, for the value of K at three and a half km, and using the variation of ρ with height given by the International Standard Atmosphere,

$$\Delta_K = 7 \times 10^{-3}\text{kj sec}^{-1}\text{m}^{-2}$$

When we compare this value of Δ_K with computations of Δ_D, the rate of total dissipation of kinetic energy by internal and surface friction in a similar unit column of atmosphere extending from the surface to ten km, we find that SVERDRUP [1918, p. 195] and BRUNT [1939, p. 286] give, as rough estimates,

$$\Delta_D = 5 \times 10^{-3}\text{kj sec}^{-1}\text{m}^{-2}$$

Thus the rate of production of kinetic energy, in our model, is of the same order of magnitude as its dissipation by friction, permitting the Westerlies to be maintained in a steady state.

This model of the general circulation of the atmosphere in the higher latitudes is based largely on indirect aerology and remains to be tested by direct synoptic means. This can be done by analyzing the vertical velocity field in individual westerly waves, using kinematic techniques. Knowledge of the vertical velocities will permit the construction of three-dimensional streamlines and from the streamlines three-dimensional trajectories can be constructed. Along each trajectory, found in this manner, the pressure and temperature of the moving air parcel can then be read as a function of time, and the image curve drawn on a thermodynamic chart, as in Figure 6. From the image curves it should be possible to compute the total rate of work production for each synoptic case.

After the kinematics and thermodynamics of the general circulation have been firmly established, there will remain the problem of describing the dynamics of the general circulation. This, of course, is a problem of no mean magnitude. But by proceeding from the known motion to the unknown forces responsible for the motion, the problem may be solved.

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A NEW STATION-TYPE MAGNETOMETER

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Abstract--This paper describes a new station-type magnetometer built with a magnetic detector based upon a saturated core-type transformer principle. The instrument is built in its most universal form, with the detector unit mounted on a somewhat special engineer's transit, and permits measurements of magnetic declination, dip, total field intensity, and horizontal and vertical components. Sensitivity is adjusted to about 10 g per division.

The Gurley-Geotechnical station-type magnetometer was developed to permit detailed analysis of magnetic phenomena associated with the Earth's field. The magnetometer was developed in the laboratories of W. and L. E. Gurley under the direct supervision of Warren C. Stoker of the Rensselaer Polytechnic Institute, assisted by A. L. Mitchell of W. and L. E. Gurley. The instrument is universal in its operation and is capable of making measurements of the Earth's magnetic field, total field intensity and direction, and the vertical and horizontal components. This instrument was intended as a tool for research to provide data for the design of more specialized instruments.

The station-type magnetometer consists of a magnetic detector mounted on a universal support, and an electronic device which translates the intelligence developed by the magnetic detector into electrical currents to operate indicating and recording instruments.

Since the detector unit is capable of making measurements of direction as well as intensity, it was necessary to give consideration to the design of the support. The telescope of an engineer's transit serves as a universal support for the detector unit. Apart from electrical and magnetic requirements, an ordinary transit will suffice. The basic transit is a Gurley No. 112, with a special three-screw leveling head to permit leveling of the instrument within five seconds. A sensitive plate level is used to permit accurate leveling (see Fig. 1).

The vertical circle is of special construction to permit accurate positioning of the detector unit within five seconds for horizontal and vertical positions. Each part of the transit was checked for magnetism, and precautions were taken to prevent eddy currents which might interfere with the operation of the detector unit.

To increase the utility of the instrument, provision is made for the mounting of a solar device that will permit rapid determinations of true azimuth within a single minute of arc. The means of measuring the intensity and direction of a magnetic field are provided by a single detector unit of special construction. Its operation is dependent upon principles developed some years ago, but the manner in which these principles are applied is somewhat new. The detector unit is essentially a saturated core-type transformer, whose core saturates in the Earth's field, in this instrument Allegheny Ludlum Mu-metal.

Figure 2 illustrates the B-H curve for a material similar to Mu-metal. A sinusoidal field is impressed on the core and, as H varies, B in the core will vary as illustrated. It will be noted that the H is high enough to over-saturate the core. As long as no d. c. component interferes with the core, B will vary in a manner similar to the input wave, except that the top of the wave is clipped caused by saturation of the core. Addition of a constant component H_e will cause a shift in the axis of the B-H curve, and close examination will show that, because of the shift, the duration of time through which the core is saturated is increased during one half of the cycle and decreased during the other half.

If the primary is wound in two equal halves in opposite directions, the voltage induced by the rate of change of B will be similar to that illustrated in Figure 3.

The voltage induced in a secondary winding by one half of the primary is illustrated as e_a and the voltage caused by the other half of the primary is shown as e_b. One will note that no voltage is induced during the period of saturation. Figure 3 illustrates a condition where no constant field is present.

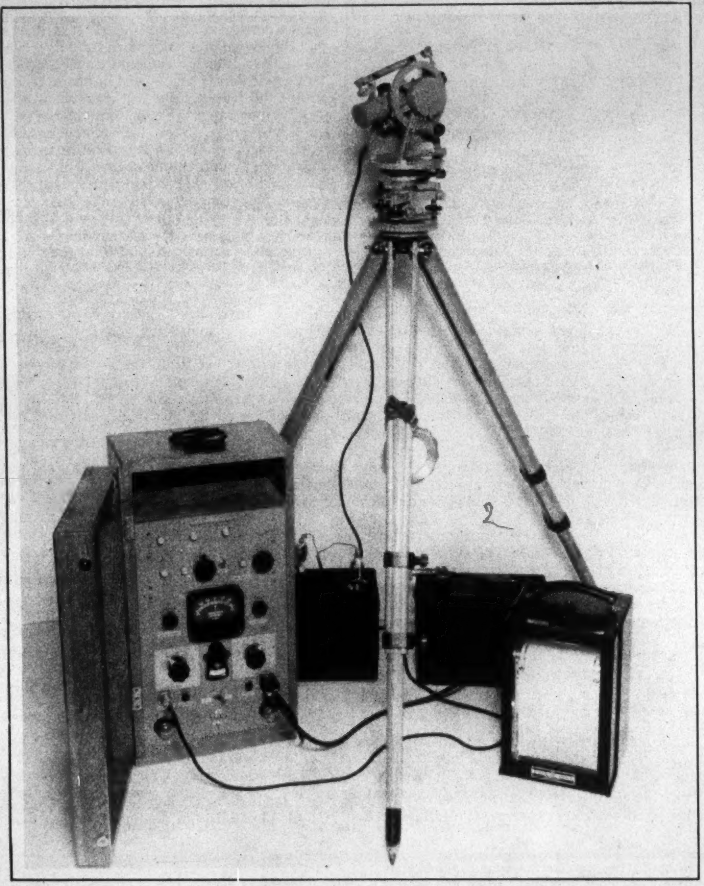

Fig. 1--Station magnetometer showing recorder

If a d. c. or steady field is added, which will cause a shift in the axis of the B-H curve, the duration of time of saturation is increased for one half of the coil, and decreased correspondingly for the other half of the coil. This results in a change of the e_a and e_b curves of Figure 3 as illustrated in Figure 4A.

Sum of the voltages $e_a + e_b$ gives rise to a voltage illustrated in Figure 4B.

With an output signal of this nature the possibility of constructing a device which is sensitive to polarity as well as to magnitude immediately becomes apparent. This magnetometer is constructed to determine polarity as well as magnitude. It is also seen that the current flow caused by a wave form illustrated in Figure 4B, is not likely to increase linearly with increases of the

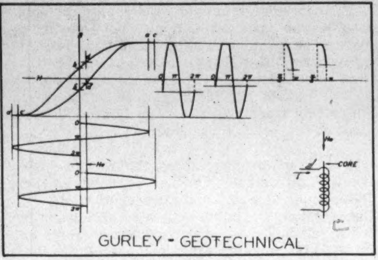

Fig. 2--Effect of H_e on core material when excited with an AC signal

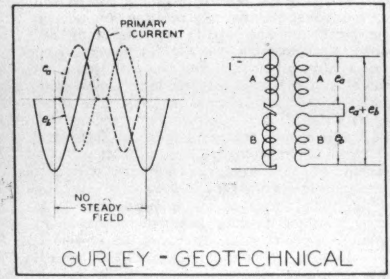

Fig. 3--Secondary output with no steady field

d. c. component, but over small ranges it can be considered to be linear. It is thus seen that the range of steady state field over which a magnetic detector can operate is limited. To keep the field impressed on the detector within the linear range, a counter d. c. field is generated to cancel out a large part of the Earth's total field. This is accomplished by passing current of a known value through a coil of wire surrounding the detector unit. That part of the instrument which is used to create the known current for the counter d. c. field is called the decade potentiometer (see Fig. 1). There are two control knobs for setting the current value. One of them is arranged in steps of 500 g through a total range of 5000 while the other one is arranged in steps of 5000 g. The total range over which adjustments can be effected is 30,000 to 80,000 g, although the design permits extension of the range from 0 to 80,000.

The precision resistors employed in the construction of the potentiometer circuit are accurate to .02 per cent. At any setting of the decade potentiometer several of the resistors are arranged in a network circuit and the overall accuracy could give errors as high as 100 g. This error can be calibrated out since the voltage supply to the potentiometer circuit is held to adequate limits.

A standard Weston cell is used as a reference of the magnitude of the voltage applied to the potentiometer decade circuit. Its voltage is compared through a suitable circuit to the input voltage of the decade potentiometer. A galvanometer is in the circuit continuously while the instrument is in operation with coarse and fine adjustments for balancing the voltages. Thus with a fine control of supply voltage, it is possible to achieve adjustments within close limits. At a given temperature, the voltages are determined accurately enough to permit a reference datum of approximately 0.5 to 1 g. Once having arrived at a series of stable magnetic field levels, determined by the decade potentiometer settings, these could be individually calibrated where higher accuracy is necessary. However, for purposes of studying anomalies, it is possible to make measurements directly to 10 g and, if higher sensitivities are required, the instrument is capable of reading less than one g.

The indicator on the control panel of the station-type magnetometer has an overall range of ± 300 g, each scale division corresponding to 10 g, with the possibility of making interpolations of each scale division.

In operating the station-type magnetometer, the magnetometer chassis and power supply are kept at a reasonable distance from the detector unit. A shielded cable of approximately 50 feet is provided in order to prevent the magnetometer chassis from causing errors of appreciable magnitude.

One of the fundamental adjustments of the detector unit itself is to align the magnetic axis of the detector unit with the optical axis of the telescope, (see Fig. 1). Simple arrangements are provided for this and, before these adjustments can be made, the transit must be in good order. Once the adjustments on the transit have been determined, it is necessary only to place the instrument telescope in a vertical position so that its optical axis is parallel with the vertical axis of the instrument. The alidade of the transit is rotated in azimuth and, if the coil is parallel with the optical axis, the signal generated by the detector unit is constant through 360° of azimuth. If the signal varies as the instrument is turned, adjustments must be made until the signal does not vary.

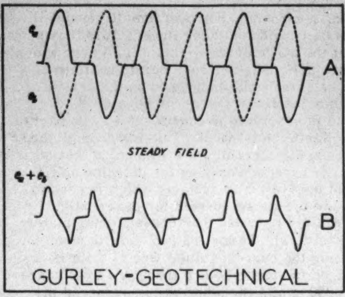

Fig. 4--Secondary outputs with steady field

The next step is to adjust the sensitivity until it matches the scale graduations. This effected by adjusting the gain of one of the amplifiers to such a value that a 500-g change, as determined by the decade potentiometer, will cause the meter hand to deflect from -250 to +250 g. A push button producing a 10 g increment is also provided. This can be used at any point on the scale.

In using the magnetometer, the instrument is set up with the detector coil in a horizontal plane as determined by reading of the transit itself. It is then rotated in azimuth until a null condition is reached, which should be at right angles to the total field. The instrument is then rotated 90° and the telescope rotated until the null is again found. This will place the detector coil at right angles to the total field, and the angle of dip can be thus measured directly. By rotating 90°, bucking out the whole field by means of the decade potentiometer setting and reading the residual on the indicator dial, the Earth's total field can be measured. Components of the Earth's total field, such as the horizontal or the vertical, can be readily measured by placing the detector coil either in the horizontal or vertical position and making measurements by means of the decade potentiometer. When the detector coil is in a null plane at right angles to the total field and, as the coil is slowly rotated into the total field, the signals generated by the detector unit will vary as the sine of the angle. Thus assuming a total field of 60,000 g and a single minute departure from the null plane, a signal of approximately 17 g would be generated and, for a single degree, approximately 1000 g. If, however, the detector coil is rotated into the maximum Earth's field, the signal will vary as the cosine of the angle and a shift of one minute is not measurable, while for 10 minutes it is approximately 0.25 g error. For one degree it is approximately 9 g. Thus in making measurements of total field, a considerable error can be tolerated in determining the null plane without having any appreciable effect on the accuracy of the measurement of the total field. In making measurements of components, however, one must be careful that precise settings of both horizontal and vertical positions are assumed since the rate of change of the sine function when working with dip angles of 45° to 70° can cause serious errors.

Temperature compensation of the device has been given consideration and materials which have low temperature coefficients of resistivity are employed wherever the need has dictated their use.

The station-type magnetometer described has been constructed in a most universal form in order that it can be applied to a variety of problems. If a continuous graphical record is desired, a standard 1-milliampere recorder can be readily inserted into the circuit (see Fig. 1). As a precaution, it must be observed that the recorder be kept at least 50 feet away from the sensitive unit because of the powerful fields of the permanent magnets employed in such recorders.

An addition of a solar unit for precise orientation would permit its use for determining accurately magnetic declination as well as dip and, with a precise calibration unit, it would be useful for making total field measurements or components thereof.

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DRIFT CURRENTS IN AN ENCLOSED SEA AND THE ROTATION OF THE EARTH

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Abstract--Surface currents and the topography of the sea surface resulting from a wind blowing over a rectangular basin of constant depth are derived. The basic equations are identical with those in Ekman's theory for wind-driven currents on a rotating globe, and the assumption of a constant Coriolis parameter, a constant eddy viscosity, and steady-state conditions have been retained. Unlike Ekman, who considered the ocean of infinite extent, the author has taken into account the effect of the boundaries. Wind velocity is assumed to vary with position, to be at a maximum in the center of the basin and zero at the up-wind and down-wind sides. Numerical values for the special case of a square basin are shown.

Introduction--In 1905 EKMAN [see "References" at end of paper, 1905] propounded that epoch-making theory of the ocean currents and elucidated the influence of the Earth's rotation on the ocean currents. According to the results obtained in his investigation, the motion of sea water on the rotating globe is directed cum sole to the force producing it.

In his investigation Ekman assumed the sea to be "infinitely wide," but he assumed the latitude to be a constant. This contradiction is necessary in order to avoid the mathematical difficulty in treating the problems, and in the author's opinion there are two means of resolving this contradiction. The first is to take the variation of latidude into account; this requires that we consider the Earth to be a rotating sphere, and use the spherical coordinates in treating the dynamics of ocean currents. This was actually tried with success by GOLDSBROUGH [1935] who showed that Ekman's solution can be applied satisfactorily only in the immediate proximities of the poles. Goldsbrough concluded that in some places the deviation is contra solem, instead of being cum sole. The second means of resolving the contradiction is to consider an enclosed sea in which variations of the latitude are neglected. This is admissive, because there are many small enclosed seas such as the Japan and Okhotsk Seas, in which the latitude can be assumed to be fairly constant; but the existence of the coasts, that is, the boundaries, can not be disregarded. In this respect the necessity of re-examining the ocean currents in an enclosed sea becomes apparent. The author has long tried to find the solution to these problems, and the following is a result of his research in this line.

Drift currents and surface slope in a rotating enclosed sea--In discussing the drift currents, it is necessary to know the distribution of the motion of the water in every depth from the surface down to the bottom, and throughout the entire basin. Much time and labor are required, however, to calculate the currents in all layers, and therefore, the discussion will be confined to the distribution of the currents and slopes on the surface of the sea.

Consider a rotating enclosed sea of uniform depth, and let the sea be a square basin, each side being a. The motion of the water is assumed to be steady after a constant, continual wind has blown for an infinitely long time. In this square sea of steady motion, there is a slope on the surface (though not exactly coincident with the direction of the wind), and a definite system of drift currents.

Take x- and y- axis, both horizontal, (see Fig. 1), the latter being positive leeward, and the former perpendicular to the right of it, and define by u and v the respective components of velocity parallel to these axes, and by δ the surface elevation above the undisturbed level.

In his theory of ocean currents, Ekman proposed a linear quantity D, given by equation 31, which he regarded as a criterion of the depth to which drift currents can occur by the influence of the winds, and defined it as "the depth of frictional influence." In our results the distribution of the drift currents depends, as in Ekman's cases, upon the magnitude of the quantity h/D, the ratio of the depth to the bottom to the depth of the frictional influence. The author here reports his results for the cases (h/D = 1/2) and h/D = 1) in the Northern Hemisphere, when the tangential stress of the wind is in the direction of y only, and is given by T sin (πy/b).

In the following expressions, ρ is the density of sea-water, g the acceleration of gravity, and $\lambda = 2\omega \sin \phi$, where ω is the angular velocity of the Earth's rotation, and ϕ is the geographical latitude.

Now we have, for $(h/D = 1/2)$, the surface slope

$$\zeta = [-0.09923 \cos(\pi x/a) - 0.41120 \cos(\pi y/a) + 0.01555 \cos(\pi x/a) \cos(2\pi y/a) + 0.00045 \cos(2\pi x/a) \cos(\pi y/a) + 0.01874 \cos(3\pi x/a) - 0.02245 \cos(3\pi y/a)](Ta/\rho gh)$$

The drift currents on the surface of the sea are given by

$$u = [0.56152 \sin(\pi x/a) - 0.18478 \sin(\pi x/a) \cos(2\pi y/a) + 0.24342 \sin(2\pi x/a) \times \cos(\pi y/a) - 0.06526 \sin(3\pi x/a)](T/\lambda\rho D)$$

and

$$v = [2.23871 \sin(\pi y/a) + 0.10459 \cos(\pi x/a) \sin(2\pi y/a) - 0.24977 \cos(2\pi x/a) \sin(\pi y/a) - 0.27839 \sin(3\pi y/a)](T/\lambda\rho D)$$

Next, for $(h/D = 1)$ we have again, for the slope and velocity components at the surface of the sea

$$\zeta = [-0.04979 \cos(\pi x/a) - 0.30554 \cos(\pi y/a) + 0.00522 \cos(\pi x/a) \cos(2\pi y/a) - 0.01754 \cos(2\pi x/a) \cos(\pi y/a) - 0.00557 \cos(3\pi x/a) - 0.03169 \cos(3\pi y/a)](Ta/\rho gh)$$

$$u = [1.41440 \sin(\pi x/a) - 1.00599 \sin(\pi x/a) \cos(2\pi y/a) + 0.04165 \sin(2\pi x/a) \cos(\pi y/a) + 0.67925 \sin(3\pi x/a)](T/\lambda\rho D)$$

$$v = [2.47882 \sin(\pi y/a) + 0.17432 \cos(\pi x/a) \sin(2\pi y/a) + 0.14751 \cos(2\pi x/a) \sin(\pi y/a) - 0.10931 \sin(3\pi y/a)](T/\lambda\rho D)$$

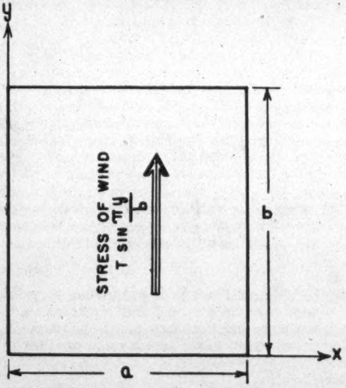

Fig. 1--Special case of a square basin: a = b

Figures 2A to 20 are diagrams showing the results given by the above formulas. Figure 2A shows the contour lines of the surface for $(h/D = 1/2)$, the figures representing the height of water above the average level measured in $Ta/\rho gh$. The water level is, of course, higher on the lee side and lower on the windward side, but it is highest and equal to 0.52 $(Ta/\rho gh)$ at the right corner of the lee side and lowest and equal to -0.52 $(Ta/\rho gh)$ at the corner opposite. Moreover, the direction of maximum slope does not coincide exactly with the leeward direction, but is slightly to the right. The amount of this deviation varies at various places, being about 22 degrees at the center of the sea, but the average over the entire sea is about 12 degrees. Figure 2B gives contours of the surface for $(h/D = 1)$. The general appearance differs only very slightly from the former case, the maximum and minimum water heights being 0.405 $(Ta/\rho gh)$ and -0.405 $(Ta/\rho gh)$, respectively. The surface deviation is about 16 degrees at the center of the sea, This is slightly smaller compared with the case $(h/D = 1/2)$.

Figures 2C and 2D show the distribution of the drift currents on the surface when $h/D = 1/2$ and $h/D = 1$, respectively, the motion of water being slight on the leeward and windward coasts and nearly constant in the direction perpendicular to the wind. Moreover, the direction of currents is, in general, deviated to the right from that of the winds, the amount being largest at the center of the sea. We have at the center of the sea. $u = 0.812\ (T/\lambda\rho D)$, and $v = 2.767\ (T/\lambda\rho D)$; and the consequent deviation of $16^\circ.35$ to the right. For $u = 1.741\ (T/\lambda\rho D)$, and $v = 2.436\ (T/\lambda\rho D)$. The deviation is $35^\circ.55$ to the right.

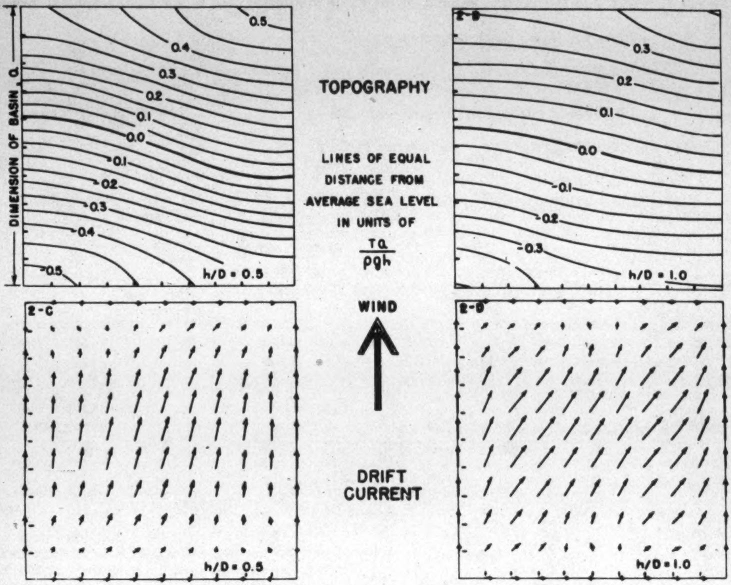

Fig. 2--Topography and drift current of a sea surface

A thing which the author did not expect is that the system of drift currents in the steady state, given above, is independent of the dimension of the sea. These results came from the assumption that the motion is so small that we can neglect $u(\partial u/\partial x)$, $v(\partial u/\partial y)$, $u(\partial v/\partial x)$, and $v(\partial v/\partial y)$ against u and v themselves, and they do not hold good when the sea is extremely small in size.

It will be interesting to compare our results with Ekman's. But the assumption that the tangential stress is given in the form $T \sin(\pi y/b)$ is different from Ekman's case where it is uniform all over the sea surface. These two assumptions become coincident at the center of the sea where $T \sin(\pi y/b)$ becomes equal to T.

Differential equations and conditions, assumptions different from Ekman's--When the wind blows over the surface of an enclosed sea, a slope always accompanies the drift currents. This is in contrast to the Ekman theory where the sea is assumed to be indefinitely wide. In a theory of an enclosed sea, Ekman assumed a constant slope in advance, which is not strictly admitted but is an inevitable consequence to avoid the mathematical difficulties. There is, of course, no reason why the slope should be uniform throughout the surface of the sea.

Consider the steady state of the sea and let the direction of the wind coincide with the positive axis of y, and take the positive x -axis perpendicularly to the right of it. Further choose the z-axis vertically downward and let z = 0 and z = h be the undisturbed top and bottom surfaces of the sea. Then the equations of motion are given in just the same way as those in Ekman's theory:

$$\left.\begin{aligned}(\kappa/\rho)(\partial^2 u/\partial z^2) + \lambda v - g\,(\partial\zeta/\partial x) = 0\\ (\kappa/\rho)(\partial^2 v/\partial z^2) - \lambda u - g\,(\partial\zeta/\partial y) = 0\end{aligned}\right\}\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

while the equation of continuity is

$$\int_0^h [(\partial u/\partial x) + (\partial v/\partial y)]\,dz = 0\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where u, v, ρ, and other terms are as previously used, κ is the coefficient of eddy viscosity and ζ is the elevation of the water surface above the mean level (z = 0) g.

On the surface (z = 0) we have the conditions

$$-\kappa\ (\partial u/\partial z) = T_x \qquad -\kappa\ (\partial v/\partial z) = T_y \quad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

where T_x and T_y are the components of tangential stress on the surface. On the bottom we have (z = h)

$$u = 0 \qquad v = 0 \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Next we must have the coastal conditions, since the sea is surrounded by land on all sides. For simplicity we assume that the sea is of a rectangular form with sides equal to a and b, respectively [see Fig. 1). Then we have the coastal conditions

$$\left.\begin{array}{ll} \text{for } x = 0 \text{ to } x = a & u = 0 \\ \text{for } y = 0 \text{ to } y = b & v = 0 \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

These coastal conditions did not appear in Ekman's theory, but they are necessary as long as we require a more strict solution of an enclosed sea, though they make the mathematical process much more complicated.

Moreover, the terms $-g(\partial\zeta/\partial x)$ and $-g(\partial\zeta/\partial y)$ in (1) are lacking in Ekman's theory, a circumstance very different from the present theory. In addition, we have the assumption that the terms $u(\partial u/\partial x)$, $v(\partial u/\partial y)$, $u(\partial v/\partial x)$, and $v(\partial v/\partial y)$ can be neglected in comparison with u and v themselves, so that it is evident that the present theory does not hold good if the sea is extremely small in size.

In the paper mentioned, Ekman discussed the drift currents in an enclosed sea, regarding the co-existence of drift currents and slope currents and determining the relation between the tangential stress and slope of the water surface, primarily supposed to be uniform, by the idea that the total flow $\int_0^h \rho u dz$ and $\int_0^h \rho v dz$, becomes zero because of the combined motion. It is evident that such an assumption is only valid if there is no variation in the velocity of the water over the entire sea. But in so far as we are discussing an enclosed sea, it is obvious that the velocity perpendicular to the coasts is zero, and there must be a horizontal gradient in the velocity of the water. Hence, Ekman's assumption ($\int_0^h \zeta u dz = \int_0^h \zeta v dz = 0$) is not correct in a strict sense, though it may be correct for some points of the sea. Thus it must be replaced by the conditions defined in (2).

Method of solution--In order to solve (1) and (2), subject to the conditions (3), (4), and (5), we put

$$\left.\begin{array}{l} u = \sum\limits_m\sum\limits_n u_{mn} \sin(m\pi x/a)\cos(n\pi y/b) \\ v = \sum\limits_m\sum\limits_n v_{mn} \cos(m\pi x/a)\sin(n\pi y/b) \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$\zeta = \sum_m\sum_n \zeta_{mn} \cos(m\pi x/a)\cos(n\pi y/b) \quad \ldots\ldots\ldots\ldots\ldots \quad (7)$$

where u_{mn} and v_{mn} are functions of z only, whereas ζ_{mn} are constants. The equations in (6) immediately satisfy the conditions (5). Substituting (6) and (7) in (1), we have

$$\sum_m\sum_n [(\kappa/\rho)(d^2u_{mn}/dz^2) + (m\pi g/a)\zeta_{mn}] \sin(m\pi x/a) \times$$
$$\cos(n\pi y/b) + \sum_m\sum_n \lambda v_{mn} \cos(m\pi x/a)\sin(n\pi y/b) = 0$$

$$\sum_m\sum_n [(\kappa/\rho)(d^2v_{mn}/dZ^2) + (n\pi g/b)\zeta_{mn}] \cos(m\pi x/a) \times$$
$$\sin(n\pi y/b) + \sum_m\sum_n \lambda u_{mn} \sin(m\pi x/a)\cos(n\pi y/b) = 0$$

and the co-existence of the terms $\sin(m\pi x/a)\cos(n\pi y/b)$ and $\cos(m\pi x/a)\sin(n\pi y/b)$ does not enable us to eliminate x and y and consequently to obtain the formulas containing u_{mn}, v_{mn}, and ζ_{mn} only.

But we have in the interval ($0 \leqq x \leqq a$; $0 \leqq y \leqq b$) the relations

$$\left.\begin{aligned} &\sum_{mn}\sum u_{mn} \sin (m\pi x/a) \cos (n\pi y/b) = \sum_{mn}\sum \Big\{ - (16/\pi^2) \sum_{rs}\sum [(rnu_{rs})/(r^2 - m^2) \times \\ &\qquad (s^2 - n^2)] \Big\} \cos (m\pi x/a) \sin (n\pi y/b) \\ &\sum_{mn}\sum v_{mn} \cos (m\pi x/a) \sin (n\pi y/b) = \sum_{mn}\sum \Big\{ - (16/\pi^2) \sum_{rs}\sum [(smv_{rs})/(r^2 - m^2) \times \\ &\qquad (s^2 - n^2)] \Big\} \sin (m\pi x/a) \cos (n\pi y/b) \end{aligned}\right\} \ldots \quad (8)$$

($r + m$ and $s + n$ are both odd), and if we substitute (6) and (7) into (1) and (2), taking these relations into account, we succeed in eliminating x and y and have

$$\left.\begin{aligned} &(\kappa/\rho)(d^2u_{mn}/dz^2) - (16\lambda/\pi^2) \sum_{rs}\sum [(smv_{rs})/(r^2 - m^2)(s^2 - n^2)] + (m\pi g/a)\, \zeta_{mn} = 0 \\ &(\kappa/\rho)(d^2v_{mn}/dz^2) + (16\lambda/\pi^2) \sum_{rs}\sum [(rnu_{rs})/(r^2 - m^2)(s^2 - n^2)] + (n\pi g/b)\, \zeta_{mn} = 0 \end{aligned}\right\} \quad (9)$$

$$(m/a) \int_0^h u_{mn} dz + (n/b) \int_0^h v_{mn} dz = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Next, the tangential stress of the wind is generally a function of x and y, so that we may put

$$\left.\begin{aligned} T_x &= \sum_{mn}\sum X_{mn} \sin (m\pi x/a) \cos (n\pi y/b) \\ T_y &= \sum_{mn}\sum Y_{mn} \cos (m\pi x/a) \sin (n\pi x/b) \end{aligned}\right\} \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

The conditions which must be satisfied by u_{mn} and v_{mn} at $z = 0$ can be derived from (3) as

$$- \kappa (du_{mn}/dz)\Big|_{z=0} = X_{mn} \qquad - \kappa (dv_{mn}/dz) = Y_{mn} \quad \ldots\ldots\ldots\ldots \quad (12)$$

and moreover, from (4), when $z = h$ we have

$$u_{mn} = v_{mn} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

Thus we could reduce the problem to the integration of the differential equations (9) only with respect to z, subject to the conditions (12) and (13), and consequent representation of u_{mn} and v_{mn} as functions of X_{mn}, Y_{mn} and ζ_{mn}, and we can find the relations between the tangential stress and surface slope by substituting u_{mn} and v_{mn} in (10).

In this way ζ_{mn}, u_{mn} and v_{mn} are all determined in terms of X_{mn}, Y_{mn}, and the problem can be solved.

But how can we integrate (9)? This can be considered as the limiting case $M \to \infty$ in the following M simultaneous equations.

$$\left.\begin{aligned} &(d^2x_1/dz^2) + a_{11}x_1 + a_{12}x_2 + \ldots\ldots + a_{1M}x_M + b_1 = 0 \\ &(d^2x_2/dz^2) + a_{21}x_1 + a_{22}X_2 + \ldots\ldots + a_{2M}x_M + b_2 = 0 \\ &\quad \cdots\cdots \qquad \cdots\cdots \qquad\qquad \cdots\cdots \quad \cdot\cdot \\ &(d^2x_M/dz^2) + a_{M1}x_1 + a_{M2}x_2 + \ldots\ldots + a_{MM}x_M + b_M = 0 \end{aligned}\right\} \ldots\ldots\ldots (14)$$

First multiply these M equations by the undetermined multipliers $\ell_1, \ell_2, \ldots, \ell_M$ and add together; then we have

$$\left.\begin{aligned} &(d^2/dz^2)(\ell_1x_1 + \ell_2x_2 + \ldots\ldots + \ell_Mx_M) \\ &\quad + (a_{11}\ell_1 + a_{21}\ell_2 + \ldots\ldots + a_{M1}\ell_M)\, x_1 \\ &\quad + (a_{12}\ell_1 + a_{22}\ell_2 + \ldots\ldots + a_{M2}\ell_M)\, x_2 \\ &\quad + \ \cdots \quad \cdots \qquad\qquad \cdots \\ &\quad + (a_{1M}\ell_1 + a_{2M}\ell_2 + \ldots\ldots + a_{MM}\ell_M)\, x_M \\ &\quad + (b_1\ \ell_1 + b_2\ \ell_2 + \ldots\ b_M\ \ell_M) = 0 \end{aligned}\right\} \ldots\ldots\ldots\ldots (15)$$

Then we introduce another unknown, ξ, and determine the quantities $\xi, \ell_1, \ell_2, \cdots \ell_M$ in the manner that satisfies the relations

$$\left.\begin{array}{l} a_{11}\ell_1 + a_{21}\ell_2 + \dots + a_{M1}\ell_M = \ell_1\xi \\ a_{12}\ell_1 + a_{22}\ell_2 + \dots + a_{M2}\ell_M = \ell_2\xi \\ \dots \quad \dots \quad \dots \\ a_{1M}\ell_1 + a_{2M}\ell_2 + \dots + a_{MM}\ell_M = \ell_M\xi \end{array}\right\} \dots\dots\dots\dots (16)$$

Then (15) becomes

$$(d^2/dz^2) \sum_{j=1}^{M} \ell_j x_j + \xi \sum_{j=1}^{M} \ell_j x_j + \sum_{j=1}^{M} \ell_j b_j = 0$$

integrating we have

$$\sum_{j=1}^{M} \ell_j x_j = -(1/\xi) \sum_{j=1}^{M} \ell_j b_j + A \exp(\sqrt{-\xi}\,z) + B \exp(-\sqrt{-\xi}\,z) \dots\dots\dots (17)$$

where ξ is one of the M roots of the equation

$$\begin{vmatrix} a_{11}-\xi & a_{21} & \dots a_{M1} \\ a_{12} & a_{22}-\xi & \dots a_{M2} \\ \dots & \dots & \dots \\ a_{1M} & a_{2M} & \dots a_{MM}-\xi \end{vmatrix} = 0 \dots\dots\dots\dots (18)$$

Let these M roots be $\xi_1, \xi_2, \dots, \xi_M$, and any of these be given by ξ_j; then $\ell_1, \ell_2, \dots, \ell_M$ depend upon ξ_j, and when we write them as

$$\ell_{1j}, \ell_{2j}, \dots, \ell_{Mj} \quad (j = 1, 2, \dots, M) \dots\dots\dots\dots (19)$$

(17) becomes

$$\left.\begin{array}{l} \ell_{11}x_1 + \ell_{21}x_2 + \dots + \ell_{M1}x_M = -(1/\xi_1)(\ell_{11}b_1 + \ell_{21}b_2 + \dots + \\ \quad \ell_{M1}b_M) + A_1 \exp(\sqrt{-\xi_1}\,z) + B_1 \exp(\sqrt{-\xi_1}\,z) \\ \ell_{12}x_1 + \ell_{22}x_2 + \dots + \ell_{M2}x_M = -(1/\xi_2)(\ell_{12}b_1 + \ell_{22}b_2 + \dots + \\ \quad \ell_{M2}b_M) + A_2 \exp(\sqrt{-\xi_2}\,z) + B_2 \exp(\sqrt{-\xi_2}\,z) \\ \dots\dots \quad \dots\dots \quad \dots\dots \quad \dots\dots \quad \dots\dots \quad \dots\dots \\ \ell_{1M}x_1 + \ell_{2M}x_2 + \dots + \ell_{MM}x_M = -(1/\xi_M)(\ell_{1M}b_1 + \ell_{2M}b_2 \\ \quad + \dots + \ell_{MM}b_M) + A_M \exp(\sqrt{-\xi_M}\,Z) + B_M \exp(\sqrt{-\xi_M}\,z) \end{array}\right\} \dots\dots (20)$$

This shows that the integration requires 2M conditions. If we consider that M becomes indefinitely large, the number of dependent variables $x_1, x_2, \dots, x_M$ also becomes larger together with the number of conditions (12) and the order of the determinant (18). Thus, our problem can be considered the limit when $M \to \infty$.

Drift currents in a rotating enclosed sea--Suppose that the enclosed sea is a rectangular shape, bounded by the coasts x = 0 to a and y = 0 to b and the wind blows in the positive direction of y (see Fig. 1). In order to simplify the problem, let us consider that all the X_{mn} and Y_{mn} are zero except $Y_{01} = T$ (constant). Thus we have

$$-\kappa (\partial u/\partial z)\Big|_{z=0} = 0 \qquad -\kappa (\partial v/\partial z)\Big|_{z=0} = T \sin(\pi y/b) \dots\dots\dots\dots (21)$$

This means that the force of the wind acts upon the positive direction of y and is constant in the direction of x. The maximum intensity is at the center (y = b/2) of the sea, gradually diminishing toward the leeward and windward coasts, a distribution of wind by no means unnatural.

The expressions for u, v, and ζ given by (6) and (7) consist of an infinitely large number of terms. But for practical computation we have only to take a few important terms into account and neglect the remaining ones. In our calculation, we assumed for u, v, and ζ as follows:

$$\left.\begin{aligned}
u &= u_{10}\sin(\pi x/a) + u_{12}\sin(\pi x/a)\cos(2\pi y/b) \\
&\quad + u_{21}\sin(2\pi x/a)\cos(\pi y/b) + u_{30}\sin(3\pi x/a) \\
v &= v_{01}\sin(\pi y/b) + v_{12}\cos(\pi x/a)\sin(2\pi y/b) \\
&\quad + v_{21}\cos(2\pi x/a)\sin(\pi y/b) + v_{03}\sin(3\pi y/b) \\
\zeta &= \zeta_{10}\cos(\pi x/a) + \zeta_{01}\cos(\pi y/b) + \zeta_{12}\cos(\pi x/a)\cos(2\pi y/b) \\
&\quad + \zeta_{21}\cos(2\pi x/a)\cos(\pi y/b) + \zeta_{30}\cos(3\pi x/a) \\
&\quad + \zeta_{03}\cos(3\pi y/b)
\end{aligned}\right\} . \quad (22)$$

and for the condition z = 0

$$\left.\begin{aligned}
&-\kappa(du_{10}/dz) = -\kappa(du_{12}/dz) = -\kappa(du_{21}/dz) = \\
&-\kappa(du_{30}/dz) = 0 \\
&-\kappa(dv_{01}/dz) = T \\
&-\kappa(dv_{21}/dz) = -\kappa(dv_{12}/dz) = -\kappa(dv_{03}\ dz) = 0
\end{aligned}\right\} \ldots\ldots\ldots\ldots \quad (23)$$

and for the condition z = h

$$u_{10} = u_{12} = u_{21} = u_{30} = 0 \qquad v_{01} = v_{12} = v_{21} = v_{03} = 0 \ \ldots\ldots\ldots\ldots \quad (24)$$

Substituting (22) in (1), we obtain the equations corresponding to (9) as in (25)

$$\left.\begin{aligned}
&(\kappa/\rho)(d^2u_{10}/dz^2) + (16\lambda/\pi^2)[\ v_{01} - v_{21}/3 + v_{03}/3] + (\pi g/a)\zeta_{10} = 0 \\
&(\kappa/\rho)(d^2u_{12}/dz^2) + (16\lambda/\pi^2)[-v_{01}/3 + v_{21}/9 + 3v_{03}/5] + (\pi g/a)\zeta_{12} = 0 \\
&(\kappa/\rho)(d^2u_{21}/dz^2) + (16\lambda/\pi^2)(4v_{12}/9) + (2\pi g/a)\zeta_{21} = 0 \\
&(\kappa/\rho)(d^2u_{30}/dz^2) + (16\lambda/\pi^2)[\ v_{01}/3 + 3v_{21}/5 + v_{03}/3] + (3\pi g/a)\zeta_{30} = 0 \\
&(\kappa/\rho)(d^2v_{01}/dz^2) - (16\lambda/\pi^2)[\ u_{10} - u_{12}/3 + u_{30}/3] + (\pi g/b)\zeta_{01} = 0 \\
&(\kappa/\rho)(d^2v_{21}/dz^2) - (16\lambda/\pi^2)[(-u_{10}/3) + (u_{12}/9) + (3u_{30}/5)] + (\pi g/b)\zeta_{12} = 0 \\
&(\kappa/\rho)(d^2v_{12}/dz^2) - (16\lambda/\pi^2)(4u_{21}/9) + (2\pi g/b)\zeta_{21} = 0 \\
&(\kappa/\rho)(d^2v_{03}/dz^2) - (16\lambda/\pi^2)[(u_{10}/3) + (3u_{12}/5) + (u_{30}/3)] + (3\pi g/b)\zeta_{03} = 0
\end{aligned}\right\} \quad (25)$$

We have only to solve these eight simultaneous differential equations of the second order subject to the sixteen assigned conditions. But a considerable simplification can be resulted if we put

$$u_{10} + iv_{01} = w_1 \qquad u_{12} + iv_{21} = w_2 \qquad u_{30} + iv_{03} = w_3 \qquad u_{21} + iv_{12} = w_4 \ \ldots \quad (26)$$

The eight equations (25) then reduce to the following four:

$$\left.\begin{aligned}
&(\kappa/\rho)(d^2w_1/dz^2) - (16\lambda i/\pi^2)[w_1 - (w_2/3) + (w_3/3)] + \\
&\qquad + \pi g[(\zeta_{10}/a) + i(\zeta_{01}/b)] = 0 \\
&(\kappa/\rho)(d^2w_2/dz^2) - (16\lambda i/\pi^2)(-w_1/3 + w_2/9 + 3w_3/5) \\
&\qquad + \pi g[(\zeta_{12}/a) + i(\zeta_{21}/b)] = 0 \\
&(\kappa/\rho)(d^2w_3/dz^2) - (16\lambda i/\pi^2)(w_1/3 + 3w_2/5 + w_3/9) \\
&\qquad + \pi g(3\zeta_{30}/a + 3i\zeta_{03}/b) = 0 \\
&(\kappa/\rho)(d^2w_4/dz^2) - (16\lambda i/\pi^2)(4w_4/9) + \pi g[(2\zeta_{21}/a) + i(2\zeta_{12}/b)] = 0
\end{aligned}\right\} \ldots\ldots \quad (27)$$

and for the condition z = 0, this becomes

$$-\kappa(dw_1/dz)\Big|_a = iT \qquad -\kappa(dw_2/dz) = -\kappa(dw_3/dz) = -\kappa(dw_4/dz) = 0 \ \ldots\ldots \quad (28)$$

and for the condition z = h

$$w_1 = w_2 = w_3 = w_4 = 0 \tag{29}$$

The fourth equation of (27) can be integrated easily, and we have

$$\begin{aligned} w_4 = (\pi^3 i/16)(9/4)(g/\lambda)\Big\{&\cosh[(1+i)(8/3)(z/D)]/\cosh[(1+i)\times \\ &(8/3)(h/D)] - 1\Big\}[(2\zeta_{21}/a) + i(2\zeta_{12}/b)] \end{aligned} \tag{30}$$

where D is Ekman's depth of the frictional influence defined by

$$D = \pi\sqrt{2\kappa/\rho\lambda} \tag{31}$$

Next we multiply the first three equations of (27) by ℓ_1, ℓ_2, ℓ_3, respectively, and add together, and we have

$$\begin{aligned} &(\kappa/\rho)(d^2/dz^2)(\ell_1 w_1 + \ell_2 w_3 + \ell_3 w_3) - (16\lambda i/\pi^2)\xi(\ell_1 w_1 + \ell_2 w_2 + \ell_3 w_3) \\ &\quad + \pi g[(\zeta_{10}/a + i\zeta_{01}/b)\ell_1 + (\zeta_{12}/a + i\zeta_{21}/b)\ell_2 + (3\zeta_{30}/a + 3i\zeta_{03}/b)\ell_3] = 0 \end{aligned} \tag{32}$$

where the ratio $\ell_1:\ell_2:\ell_3$ and ξ must be determined by the three equations

$$\left.\begin{aligned} (1 = \xi)\ell_1 - \ell_2/3 + \ell_3/3 &= 0 \\ -\ell_1/3 + (1/9 - \xi)\ell_2 + 3\ell_3/5 &= 0 \\ \ell_1/3 + 3\ell_2/5 + (1/9 - \xi)\ell_3 &= 0 \end{aligned}\right\} \tag{33}$$

solving these equations we have three roots of ξ. They are

$$\left.\begin{aligned} \xi_1 &= (-\sqrt{6289} + 23)/90 = -\,0.6255913 \\ \xi_2 &= 64/90 \qquad\qquad\quad\;\; = +\,0.7111111 \\ \xi_3 &= (\sqrt{6289} + 23)/90 \quad\;\, = +\,1.1367024 \end{aligned}\right\} \tag{34}$$

while the ratios $\ell_1:\ell_2:\ell_3$: are

$$\left.\begin{aligned} \ell_{11}:\ell_{21}:\ell_{31} &= 60:67 + \sqrt{6289}: -67 - \sqrt{6289} = -\,0.4101072: -1:1 \\ \ell_{12}:\ell_{22}:\ell_{33} &= 0:1:1 \\ \ell_{13}:\ell_{23}:\ell_{33} &= 60:67 - \sqrt{6289}: -67 + \sqrt{6289} = \;\; 4.876773 : -1:1 \end{aligned}\right\} \tag{35}$$

Integrating (32) subject to the conditions (28) and (29) we have

$$\left.\begin{aligned} \ell_1 w_1 + \ell_2 w_2 + \ell_3 w_3 = (i\pi^3/16)(g/\lambda)[(&\zeta_{10}/a + i\zeta_{01}/b)\ell_1 \\ &+ (\zeta_{12}/a + i\zeta_{21}/b)\ell_2 + (3\zeta_{30}/a + 3i\zeta_{03}/b)\ell_3]\Big\{\cosh[(1+i)\times \\ &(4\sqrt{\xi})(h/D)(z/h)]/\cosh[(1+i)4\sqrt{\xi}(h/D)] - 1\Big\} \\ &+ [(1+i)/8\sqrt{\xi}][(DT/\kappa)]\ell_1\Big\{\sinh[(1+i)4\sqrt{\xi}(h/D)(1 - z/h)]/ \\ &\cosh[(1+i)4\sqrt{\xi}(h/D)]\Big\} \end{aligned}\right\} \tag{36}$$

where D is given by (31). Substituting in this equation the three values of ξ and corresponding ratios $\ell_1:\ell_2:\ell_3$ given by (35) in order, we have the following three equations:

$$\left.\begin{aligned} -\,0.4101072w_1 - w_2 + w_3 = (g/\lambda)\Big\{&-0.4101072(\zeta_{10}/a + i\zeta_{01}/b) \\ &- (\zeta_{12}/a + i\zeta_{21}/b) + (3\zeta_{30}/a + 3i\zeta_{03}/b)\Big\}(P_1 + iQ_1) \\ &- 0.4101072\,(DT/\kappa)(M_1 + iN_1) \\ w_2 + w_3 = (g/\lambda)[(\zeta_{12}/a + i\zeta_{21}/b) &+ (3\zeta_{30}/a + 3i\zeta_{03}/b)](P_2 + iQ_2) \\ 4.876773w_1 - w_2 + w_3 = (g/\lambda)[&4.876773\,(\zeta_{10}/a + i\zeta_{01}/b) - (\zeta_{12}/a \\ &+ i\zeta_{21}/b) + (3\zeta_{30}/a + 3i\zeta_{03}/b)](P_3 + iQ_3) + 4.876773\,(DT/\kappa) \\ &(M_3 + iN_3) \end{aligned}\right\} \tag{37}$$

where

$$M_j + iN_j = [(1 + i)/(8\sqrt{\xi_j})] \sinh [(1 + i)4\sqrt{\xi_j}(h/D)(1 - z/h)]/\cosh [(1 + i)4\sqrt{\xi_j}(h/D)] \;.\,.\; (38)$$

$$P_j + iQ_j = (i\pi^3/16\xi_j)\left\{\cosh [(1 + i)4\sqrt{\xi_j}(h/D)(z/h)]/\cosh [(1 + i)4\sqrt{\xi_j}(h/D)] - 1\right\} \;.\,.\,.\,.\; (39)$$

Separating the real and imaginary parts of (30) and (37), we have

$$\left.\begin{aligned}
u_{10} &= (g/\lambda)[p_1(\zeta_{10}/a) - q_1(\zeta_{01}/b) + p_2(\zeta_{12}/a) - q_2(\zeta_{21}/b) - 3p_2(\zeta_{30}/a) \\
&\quad + 3q_2(\zeta_{03}/b)] + (DT/\kappa)m_1 \\
u_{12} &= (g/\lambda)[- p_2(\zeta_{10}/a) + q_2(\zeta_{01}/b) + p_3(\zeta_{12}/a) - q_3(\zeta_{21}/b) + 3p_4(\zeta_{30}/a) \\
&\quad - 3q_4(\zeta_{03}/b)] + (DT/\kappa)m_2 \\
u_{21} &= (g/\lambda)[(- 2a/b)\; Q_4\,(\zeta_{12}/a) + (2b/a)P_4(\zeta_{21}/a)] \\
u_{30} &= (g/\lambda)[p_2(\zeta_{10}/a) - q_2(\zeta_{01}/b) + p_4(\zeta_{12}/a) - q_4(\zeta_{21}/b) + 3p_3(\zeta_{30}/a) \\
&\quad + 3q_3(\zeta_{03}/b)] - (DT/\kappa)m_2 \\
v_{01} &= (g/\lambda)[q_1(\zeta_{10}/a) + p_1(\zeta_{01}/b) + q_2(\zeta_{12}/a) + p_2(\zeta_{21}/b) + 3q_2(\zeta_{30}/a) \\
&\quad - 3p_2(\zeta_{03}/b)] + (DT/\kappa)n_1 \\
v_{12} &= (g/\lambda)[(2a/b)P_4(\zeta_{12}/a) + (2b/a)Q_4(\zeta_{21}/b)] \\
v_{21} &= (g/\lambda)[- q2(\zeta_{10}/a) - p_2(\zeta_{01}/b) + q_3(\zeta_{12}/a) + p_3(\zeta_{21}/b) + 3q_4 \times \\
&\quad (\zeta_{30}/a) + 3p_4(\zeta_{03}/b)] + (DT/\kappa)n_2 \\
v_{03} &= (g/\lambda)[q_2(\zeta_{10}/a) + p_2(\zeta_{01}/b) + q_4(\zeta_{12}/a) + p_4(\zeta_{21}/b) + 3q_3 \times \\
&\quad (\zeta_{30}/a) + 3p_3(\zeta_{03}/b)] - (DT/\kappa)n_2
\end{aligned}\right\} \;.\,.\; (40)$$

where

$$\left.\begin{aligned}
p_1 &= 0.0775707\,P_1 && + 0.9224292\,P_3 \\
p_2 &= 0.1891474\,P_1 && - 0.1891474\,P_3 \\
p_3 &= 0.4612146\,P_1 + 0.5\,P_2 && + 0.0387854\,P_3 \\
p_4 &= - 0.4612146\,P_1 + 0.5\,P_2 && - 0.0387854\,P_3 \\
q_1 &= 0.0775707\,Q_1 && + 0.9224292\,Q_3 \\
q_2 &= 0.1891474\,Q_1 && - 0.1891474\,Q_3 \\
q_3 &= 0.4612146\,Q_1 + 0.5\,Q_2 && + 0.0387854\,Q_3 \\
q_4 &= 0.4612146\,Q_1 + 0.5\,Q_2 && - 0.0387854\,Q_3 \\
m_1 &= 0.0775707\,M_1 && + 0.9224292\,M_3 \\
m_2 &= 0.1891474\,M_1 && - 0.1891474\,M_3 \\
n_1 &= 0.0775707\,N_1 && + 0.9224292\,N_3 \\
n_2 &= 0.1891474\,N_1 && - 0.1891474\,N_3
\end{aligned}\right\} \;.\,.\,.\,.\,.\,.\,.\; (41)$$

Next we must substitue the values of u_{mn} and v_{mn} given by (40) in (10), that is, in

$$(m/a) \int_0^h u_{mn}(z)dz + (n/b) \int_0^h v_{mn}(z)dz = 0 \;.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\,.\; (42)$$

then we have the following six equations, taking the relations $u_{10} = v_{01} = u_{30} = v_{03} = 0$ into account.

$$\left.\begin{aligned}
\bar{p}_1(\zeta_{10}/a) - \bar{q}_1(\zeta_{01}/b) + \bar{p}_2(\zeta_{12}/a) - \bar{q}_2(\zeta_{21}/b) - 3\bar{p}_2(\zeta_{30}/a) + 3\bar{q}_2(\zeta_{03}/b) &= - \bar{m}_1(\lambda DT/\kappa g) \\
\bar{q}_1(\zeta_{10}/a) + \bar{p}_1(\zeta_{01}/b) + \bar{q}_2(\zeta_{12}/a) + \bar{p}_2(\zeta_{21}/b) - 3\bar{q}_2(\zeta_{30}/a) - 3\bar{p}_2(\zeta_{03}/b) &= - \bar{n}_1(\lambda DT/\kappa g) \\
\bar{p}_2(\zeta_{10}/a) - \bar{q}_2(\zeta_{01}/b) + \bar{p}_4(\zeta_{12}/a) - \bar{q}_4(\zeta_{21}/b) + 3\bar{p}_3(\zeta_{30}/a) - 3\bar{q}_3(\zeta_{03}/b) &= + \bar{m}_2(\lambda DT/\kappa g) \\
\bar{q}_2(\zeta_{10}/a) + \bar{p}_2(\zeta_{01}/b) + \bar{q}_4(\zeta_{12}/a) + \bar{p}_4(\zeta_{21}/b) + 3\bar{q}_3(\zeta_{30}/a) + 3\bar{p}_3(\zeta_{03}/b) &= + \bar{n}_2(\lambda DT/\kappa g)
\end{aligned}\right\} (43)$$

$$\left.\begin{aligned}&\bar{p}_2(\zeta_{10}/a) - \bar{q}_2(\zeta_{01}/b) + [\bar{p}_3 + 4(a^2/b^2)\bar{P}_4](\zeta_{12}/a) + (-\bar{q}_3 + 4\bar{Q}_4)(\zeta_{21}/b) + 3p_4(\zeta_{30}/a)\\ &\quad - 3\bar{q}_4(\zeta_{03}/b) = -\bar{m}_2(\lambda DT/\kappa g)\\ &\bar{q}_2(\zeta_{10}/a) + \bar{p}_2(\zeta_{01}/b) + (q_3 - 4\bar{Q}_4)(\zeta_{12}/a) + [\bar{p}_3 + 4(b^2/a^2)\bar{P}_4](\zeta_{21}/b) + 3\bar{q}_4(\zeta_{30}/a)\\ &\quad + 3\bar{p}_4(\zeta_{03}/b) = -\bar{n}_2(\lambda DT/\kappa g)\end{aligned}\right\}\text{(43), concluded}$$

where the barred terms show the average quantities given by

$$\left.\begin{aligned}&\bar{p}_1 = (1/h)\int_0^h p_1 dz \;\ldots, \bar{p}_4 = \int_0^h p_4 dz\\ &\bar{q}_1 = (1/h)\int_0^h q_1 dz \;\ldots, \bar{m}_1 = (1/h)\int_0^h m_1 dz,\ \bar{m}_2 = (1/h)\int_0^h m_2 dz\\ &\bar{n}_1 = (1/h)\int_0^h n_1 dz \;\ldots, \bar{P}_1 = (1/h)\int_0^h P_1 dz, \ldots\end{aligned}\right\} \ldots\ldots (44)$$

Now that $\bar{p}_1, \bar{p}_2, \ldots, \bar{q}_1, \bar{q}_2, \ldots, \bar{m}_1, \bar{m}_2, \bar{n}_1, \bar{n}_2$ are all constants, we obtain

$$(\zeta_{10}/a), (\zeta_{01}/b), (\zeta_{12}/a), (\zeta_{21}/b), (\zeta_{30}/a), (\zeta_{03}/b) \ldots\ldots\ldots\ldots (45)$$

solving (44) as simultaneous equations. Substituting (45) in the third equation of (22) we can determine the surface elevation ζ.

Moreover, if we substitute these in (40), we can determine u_{01}, u_{12}, u_{21}, u_{30} and v_{01}, v_{12}, v_{21}, v_{03} as the functions of z, which give, on substituting in the first and second equation of (22), the distribution of drift currents u and v as functions of x, y, and z.

The problem of drift currents in a rotating enclosed sea has thus been solved. To obtain more exact results, we must add some more terms besides those adopted in (22). But in our calculation we shall satisfy ourselves with the foregoing degree of approximation.

At the beginning of this dissertation, we gave the results for the surface slope and drift currents in a square sea for h/D = 1/2, and h/D = 1. They were obtained as the results of the above-mentioned calculations.

Summary--Ekman, discussing the drift currents in an indefinitely wide ocean, supposed the latitude to be a constant, a necessary assumption to avoid mathematical difficulties. In this paper the rotating sea was assumed to be landlocked and not so large in size, so that the latitude is fairly constant within it.

In an enclosed sea we need the assumption that the current components perpendicular to the coasts are nil. This makes the mathematical treatment far more complicated. The present research attempts to solve the problem of drift currents in an enclosed sea under this assumption.

The author supposed, besides the assumptions used by Ekman, that the tangential stress on the surface is given in the form [T sin (πy/b)], and especially executed the numerical computations for a square sea on a rotating surface. The results are given in Figure 2.

From our results it may be concluded that the system of drift currents solely depends upon the ratio h/D and is independent of the linear dimensions of the rotating sea.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM MAY 4 TO SEPTEMBER 8, 1946

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U. S. Department of the Interior.)

The eruptive activity of Parícutin Volcano has been classified by Ezequiel Ordóñez and Ariel Hernández Velasco into three phases, each seeming to follow the other in succession: (1) The tubular eruption, consisting of explosive reports as if from tube-like cannons, synchronized with puffs of vapor and forming a column charged with much pyroclastic material; (2) the silent eruption, varying from rolling, thunder-like explosions, deep and subdued, through periods of complete silence, to rare noises like the faint beating of the surf, accompanied by the emission of considerable pyroclastic material; and (3) the gaseous eruption, characterized by a steady noise like that of escaping steam, during which white vapors are emitted; at times, stained yellow with traces of ash.

KENNEDY [see "Reference" at end of paper, 1946] described the activity as having been very weak from April 30 to May 3, following an earlier period of strong eruption. On the afternoon of May 3, the third phase of the above succession started with a steady steam-escape roar accompanied by the emission of light vapors or none at all. This continued through May 5.

On May 6 phase 1 began again, with a tubular eruption characterized by a black column that was as full of ejecta as in March, 1943. On the next day there was virtual silence, but some pyroclastic material was erupted. On May 8 this turned into another gaseous phase, which lasted until noon of May 13, when a renewal of strong activity was heralded by puffs of vapor and deep explosions. This tubular phase lasted until May 20, and the emission of pyroclastic material was so great that a part of the southeast rim of the crater rose about 20 m in height, nearly attaining the altitude of the east peak. The silent eruption that followed continued nearly to the end of the month, gradually giving way to a gaseous eruption with its characteristic emission of white vapors.

Of the three vents in the crater described by Kennedy, the southwest one contributed most of the ejecta during the May 13-20 eruption, whereas the gaseous activity at the end of May came from the small central vent, causing it to become larger at the expense of its neighbors, both of which were quickly stopped up and covered. During the first days of June the east peak became incrusted with white salts. The southwest vent blew open again, emitting vapors that were generally more yellowish than those from the central vent. Some 15 m southwest of the central vent and about five m lower, a small, new vent opened which emitted puffs of reddish vapor. This new vent had completely disappeared by the middle of June.

Another cycle began on June 11, starting with a tubular eruption marked by typical periodic explosions and accompanied by a fall of ash, scoria, and bombs, becoming silent on June 18; occasional puffs of vapor occurred with weak, rolling explosions. Then on June 21 the gaseous stage reappeared. On the next day periodic explosive reports were noted, and with the strongest ones, some rocks were thrown out. The tubular activity increased in strength, except for an unnatural calm from June 27 to 30, until it culminated on the night of July 2 in bomb-throwing comparable to the earlier, more active years. This phase was actually a multiple one, for the central and southwest vents were frequently active together, the former emitting white vapors with a roar of escaping steam and the latter sending forth yellowish, grayish, or reddish vapors colored by ash and scoria.

The comparatively silent eruption that observers have grown to expect as a transition between the tubular and gaseous phases lasted only through July 4. From July 5 to 31 occurred an unusually long period of gaseous activity. The white vapors accompanied by a steady steam-escape sound that usually mark this phase rose invisibly to some hundreds of meters above the crater, where they then condensed to form a cumulus cloud (see Fig. 1). Only when the relative humidity of the atmosphere was high, as in the afternoons and especially at dawn, was the vapor visible all the way down to the crater. The southwest vent and the long-dormant northeast vent remained inactive.

Figure 1--Photograph of Parícutin Volcano from near San Juan, showing the cumulus cloud of vapor detatched from its source in the crater

During July the relatively quiet, southwest vent exposed to view its vertical-walled throat of agglomerate. The northeast vent remained closed under a thickening pile of red talus, and faults with as much as two m of displacement developed among the fissures that encircled it. The central vent had opened to about ten m in diameter, exhibiting the agglomerate-walled throat from which the gaseous eruption emerged. At moments of diminished sound, a few ejecta were hurled out. At the end of July increasing amounts of yellow and white sublimates were noted around the concentric fissures spaced two to three m apart that lined the inside of the crater. From these cracks rose a colorless gas with an odor mostly of SO_2, rarely of H_2S. On the map of the crater (Fig. 2) made on July 27, the two open vents, B and C, are shown by small concentric rings. A is the talus-covered site of the northeast vent, which formed a slight depression; D is the site of the short-lived explosive vent seen early in June; E is the saddle in the northeast inner rim; and F is the saddle in the southwest rim. F was an inner-rim site until the slump of March 17, which destroyed the southwest outer rim that had earlier occupied approximately the position GH. Points E, S, and 2738 rose during April and May, but T, the saddle in the northeast outer rim, rose scarcely at all. The largest fault fissure on the inner north rim of the crater is shown on the map, but many other fissures that lined the inner crater walls at that time are not shown.

The renewed activity of the crater during August was in striking contrast to the comparative quiescence during July. The steady steam-escape noise from the eruption grew more erratic on August 2. The whiteness of the vapors became dirtied by a thin veil of ash, and at night there was more incandescence than had been seen for a month. A transition period from gaseous to tubular eruption occurred during the night of August 4-5, ushering in a tall incandescent column bearing large quantities of ash and bombs, but accompanied only briefly by the usual loud tubular reports. Periods of silence were noted on August 5, but a heavy emission of pyroclastics continued, mostly accompanied by rolling explosions but featuring, on August 6, loud pounding noises like those of a switch locomotive. On August 6 and 7 compression waves made pulsating flashes that could be seen over the top of the crater for great distances. During an absence of the writers, Ariel Hernández Velasco reported that the tubular eruption continued from August 9 to 13, with an ash-and-bomb-charged column that on August 13 lifted ash as high as three km, and with reports that on August 11 and 12 were heard as far away as the city of Uruapan.

The phase of strong activity lasted through August 25, but of varying nature, featuring characteristics of both the tubular and silent eruptions. It ranged from long periods of silence, as on August 14 and 15, through brief but earth-shaking reports at irregular intervals of several minutes, as on August 22, to rolling thunderous explosions lasting four to five seconds and closely spaced, as on August 25. All the eruptive variations during this period produced great amounts of ash. East winds, typical of the rainy season, carried almost all the ash westward and northwestward from the cone. On August 24 the column of vapors was dropping appreciable loads of dust as far as 50 km to the northwest. New ash was deposited every day at the Lower Casita near San Juan, making turbid the rain water that was collected from the roof. Rain gages at both Jarátiro and San Juan frequently showed several mm of ash from one observation to the next.

August 26 dawned with a gaseous explosion. The steam-escape sound was continuous but variable in intensity throughout the rest of the month, as was the usually thin white vapor column, which varied from brief periods of invisibility to an occasional thick yellowish column. On rare occasions a double column was noted, and observations from the top of the cone on August 28 showed that the respective roles of the two eruptive vents seemed to have been reversed since the month before, the more yellowish vapors now coming from the central vent instead of from the southwest one.

On August 28 the west base of the cone was seen to be deeply littered with fragments averaging ten cm in diameter, from the August bomb showers. Slightly up the slopes were broad talus cones of lapilli, uniformly about one cm in diameter. From the summit rim of the cone the central vent was seen to have broadened, but the southwest and northeast vents had not changed during the month. Only ephemeral white vapors issued from the southwest vent and none, of course, from the buried northeast vent, but the central one discharged yellowish vapors, composed mostly of water

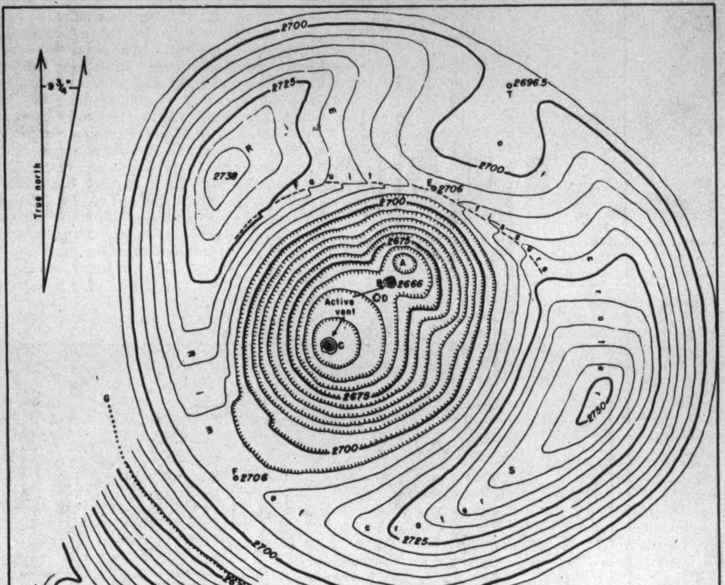
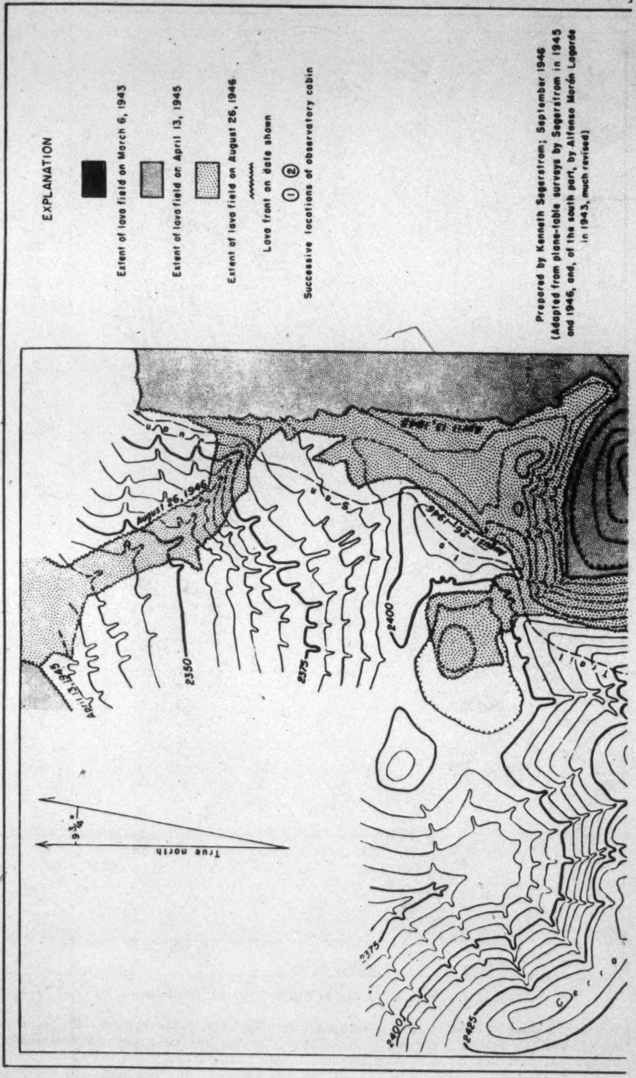

True north
9 3/4°
2700
2725
2738
2696.5
2706
2675
2666
2750
2637
2626
2597
2650
2625
2600
2588
Active vent
A
B
C
D
E
F
G
H
R
T
Fault
Fissure
Fault fissure
Rim of crater
Base of cone
"Large hornitos"
Fissure over crusted lava stream
Lava boca
Fresh lava stream
100
0
200 meters
Contour interval 5 meters; datum sea level
Surveyed by Kenneth Segerstrom; July 27, 1946

Figure 2--Map of the crater, Parícutin Volcano

but bearing some ash and lapilli, accompanied by the usual gaseous roar. The strong August eruption had built up the inner north rim about 16 m, leaving the outer edge not noticeably changed.

On September 1 another cycle of activity was entered into, beginning with the renewal of a sometimes tubular-like, sometimes silent eruption, often featuring low, deep rumbling explosions


EXPLANATION
Extent of lava field on March 6, 1943
Extent of lava field on April 13, 1945
Extent of lava field on August 26, 1946
Lava front on date shown
① ② Successive locations of observatory cabin
April 13, 1945
August 26, 1946
2350
2375
2400
2425
True north
9¾°

Prepared by Kenneth Segerstrom; September 1946
(Adapted from plane-table surveys by Segerstrom in 1945 and 1946, and, of the south part, by Alfonso Morán Lagarde in 1943, much revised)

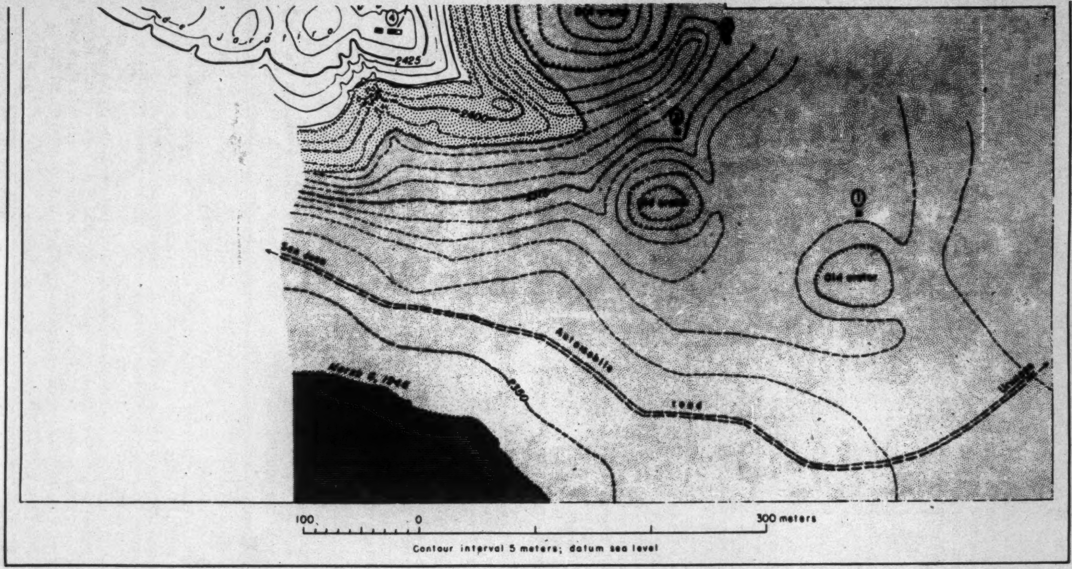

2425
2400
2350
Old crater
Old crater
San Juan
Automobile
road
100
0
300 meters
Contour interval 5 meters; datum sea level

Fig. 3--Topographic map at Cerro de Jarátiro, vicinity of Parícutin Volcano, State of Michoacan, Mexico, showing extent of lava field on March 6, 1943, April 13, 1945, and August 26, 1946 with much emission of bombs, which on September 6 soared obliquely to the north and landed far down the sides of the cone. A short-lived gaseous eruption on September 7 turned the next day into a new, equally brief tubular phase, consisting of very deep, intermittent explosions. During the night of September 8, a nearly inaudible fountain of incandescent material rose and fell for hours, not once dying down completely. The next morning enormous bombs showered the west side of the crater, one of which, two m in diameter, was observed to land at the west base. The silent phase this time continued until September 15, accompanied by appreciable amounts of new ash, which was deposited to the west, and by a sound varying from that of beating surf, on September 12, to complete silence on the two succeeding days.

On the afternoon of September 15, the loud continuous roar so well known by now began again. By September 18, the characteristic whitish vapors were tinged with yellow again, and short cessations of the roaring noise were accompanied by showers of small bombs. The following altitude determinations of the crater made on September 16 should be compared with those in Figure 2: east peak 2750.9, west peak 2747.6, north inner rim 2726.3.

A visit to the cone on September 18 revealed that the west base had been blanketed with ten cm of new ash in the previous three weeks, covering bomb fragments and the adjacent lava. The central explosive vent, which originally occupied a ridge-top position between the broader northeast and southwest vents had grown very broad and deep. The depression marking the defunct northeast vent had disappeared altogether, as had the ridge between it and the southwest vent. However, three eruptive throats were still in evidence. On a narrow shelf part way up the side of the great central throat, thin slow-moving white vapors drifted up from the nearly destroyed old southwest vent, and on a yet narrower bench across the central throat to the northeast, a lusty new vent was shooting out a strong jet of steam. The latter, with a diameter of two m, was much smaller and situated much lower than the old northeast vent. A vertical wall of agglomerate 20 m high descended from the new vent to the floor of the central throat, 80 m below the average of the crater rim. The inner south rim showed a great broadening inward toward the center. The growing west peak had attained a knife-edge profile, dropping steeply on both sides and built of loose, very fine ash. Some development of a new bench on the east side of the inner crater was noted. Abundant yellow and orange sublimates had formed on the east peak, and from very narrow fissures whitish vapors smelling of SO_2 streamed out.

In the following report on lava activity, the Quiquichio boca[a] of the KENNEDY [1946] report is referred to by its older, more common name, which is Ahuán. The date in line three of the second paragraph under "Lava Flows" in the same report should read April 3 instead of March 3.

Of the two branches of the lava flow that emerged from the rejuvenated Ahuán boca on March 17, one was four km northeast of the cone by May 6, and the other had almost reached the base of the hill of the Upper Casita. The lava stream at and near its source had by May 14 sunk into a trench two to four m deep and 15 m wide, along the south base of the cone. Five days later a collapse of the walls buried the still-active flow for the first 100 m from its source.

By May 26 part of the lava was emerging 50 m south of the original exit, and 100 m to the east, as described above. Between the foot of the cone and the south exit, a row of four hornitos emitting a steady roar had developed. By May 31 the southernmost exit of lava was 100 m south of the cone, and new spatter cones occupied the intervening distance. At this time the speed of the flow at the boca was about nine m per minute, and the speed of the moving fronts of lava varied from one half to four m per hour.

By June 12 the flow at the base of the Upper Casita hill had stopped, but the northeastern lava front was moving at two m per hour. Ten days later it had reached its point of greatest advance over the old San Juan flow, not far from where the trail from San Juan to the Upper Casita crossed it. On June 26 a new branch of the stream of lava moving at the east base of the cone started toward Zapichu, and two days later it had again surrounded this satellite cone, now nearly buried in the successive flows that had passed it. At its front the new stream had a speed of 15 m per hour on June 28, and 10 m per hour the next day. During June the line of puffing hornitos at Ahuán gradually became more quiet. The lava in the south Ahuán boca rose and fell rhythmically during periods of observation, while the boca area itself rose about four m above the adjacent lava field. The long northeast flow, sapped by its vigorous Zapichu branch, had become completely inactive by July 3, but the active branch stream had again reached the base of the Upper Casita hill by the next day, moving at 5 m per hour at its front.

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[a] The word "boca" denotes a feature which differs in no way from a vent but it is so deeply ingrained in local usage that it is retained here.

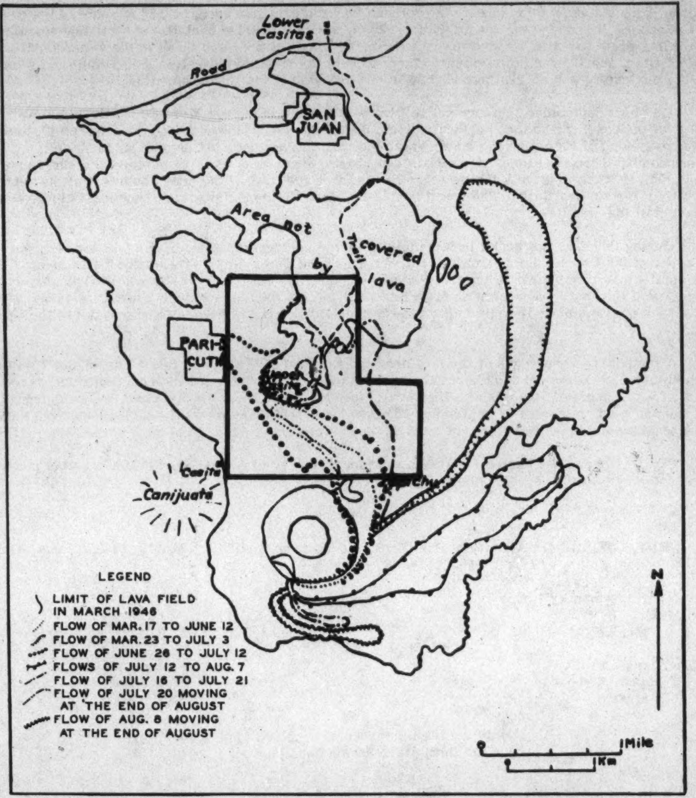
Lower Casitas
Road
SAN JUAN
Area not covered by lava
Trail
PARI-CUTIN
Caojita
Canijuata
Zapichu
LEGEND
LIMIT OF LAVA FIELD IN MARCH 1946
FLOW OF MAR. 17 TO JUNE 12
FLOW OF MAR. 23 TO JULY 3
FLOW OF JUNE 26 TO JULY 12
FLOWS OF JULY 12 TO AUG. 7
FLOW OF JULY 16 TO JULY 21
FLOW OF JULY 20 MOVING AT THE END OF AUGUST
FLOW OF AUG. 8 MOVING AT THE END OF AUGUST
N
0
1 Mile
0
1 Km

Fig. 4--Sketch map of Parícutin lava flows, March 17 to August 31, 1946
(This map is based on Fig. 3, p. 409, Transactions, June, 1946. A small flow on the west side, which ceased at its boca on March 18 and at its front on April 4, is omitted).

On July 12 a new tongue was observed to head eastward from the base of the cone, almost immediately sapping all the flow from the northern tongue of June 26. On about July 16 the lava emerging from the south end of the row of Ahuán hornitos stopped adding its stream to the more easterly, buried flow, and sent a new tongue southeastward for five days. On June 20 a new flow darted northward from the east side of the cone, repeating the route past Zapichu much traveled by earlier flows, draining away the source flow of the east tongue of July 12. By August 7 the latter came to a halt, after invading half the area of a small peninsula of virgin ground about 3 km east of the cone. By the end of July the southernmost exit of the Ahuán lava was 170 m from the base of the cone (see Fig. 2).

During August the flow north of Zapichu developed four distinct lobes in the vicinity of the Upper Casita. The topographic map of Cerro de Jarátiro (Fig. 3) shows the details of the lava inundation here from March 6, 1943, onward. On about August 8 a new lava flow started from the

Ahuán hornitos about 50 m nearer the volcano than the previous boca, or 120 m south of the base of the cone. Its course was westward for 125 m, where it doubled back to the south and southeast in a great bow that seemed to touch the outer limits of previous flows in the vicinity. At the same time, short-lived flows emerged from each of the first three spatter cones south of the volcano, coalescing and congealing about 30 m on each side of the line of hornitos.

On about September 11 a new active lava boca opened in the old Mesa de los Hornitos area, west of the cone. Since the spectacular slumping of the south side of the cone on March 17, and the re-issuing of lava from the Ahuán area, the only activity seen for months on Mesa de los Hornitos had been the gradual forming of a hogback ridge rising up to 15 m above the surrounding cold lava field. In one week the new flow had reached the base of the hills southwest of the outer limits of the earlier flows. The broad front sent lobes to the northwest and southeast along the margin of the lava field.

During the first two weeks in September only the southernmost one of the four lobes in the vicinity of the Upper Casita remained active. This lobe was fed by a stream about five m wide that originated near the base of a fumarole-topped hill between the Upper Casita and the volcano, and it followed the south and west base of Jarátiro hill. From the same source a newer, smaller lobe was seen on September 16 to be riding slowly over old lava a few hundred meters east of the Upper Casita.

A temporary resurgence of the lava near the east end of the flow of July 12 to August 7 was on September 18 sending out two short narrow lobes over old lava, toward the remaining uncovered part of a peninsula of virgin land. The boca of the flow south from Ahuán, which had commenced on August 8, had migrated by September 18 about 50 m south, and the still-moving lava front had advanced to a point approximately due south of the eastern-most edge of the base of the cone.

Figure 4 shows the Parícutin lava flows from March 17 to August 31, 1946; it does not include the September flows described above.

Reference

KENNEDY, GEORGE D., Activity of Parícutin Volcano from April 12 to May 3, 1946, Trans., Amer. Geophys. Union, v. 27, pp. 410-411, 1946.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM SEPTEMBER 18 TO NOVEMBER 30, 1946

Ray E. Wilcox

(Published by permission of the Director, U. S. Geological Survey)

The following is a summary of observations of the activity of Parícutin Volcano, Michoacan, Mexico, from the time of the writer's arrival there, September 18, until November 30, 1946, and continues the account of the preceding period by SEGERSTROM and GUTIÉRREZ [see "References" at end of paper, 1947].

This report consists primarily of the graph of eruptive characteristics, Figure 1, and lava-flow maps, Figures 2 to 4. Since most of the generalities and details of the activity can be obtained by examination of these figures, the written portion of the report will deal only with points of special interest in the figures and with information not there represented.

Graph of eruptive characteristics--Figure 1 shows graphically the day-by-day variations in the activity of the Volcano together with other possibly related phenomena. While the time scale of Figure 1 is quantitative, the values expressed on the ordinate scales of those portions pertaining to the eruptive activity itself are necessarily qualitative. In setting up convenient ordinate scales for the amounts of lava and pyroclastics, the expression "very great" was chosen to represent the same order of magnitude as that of the most intense eruption of Parícutin Volcano in the past. The measure of this quantity was established by co-observation and discussion with several long-time observers of the Volcano, notably Ezequiel Ordoñez and Celedonio Gutiérrez.

The height of the eruptive column may be taken as a rough measure of the kinetic and thermal energy of the eruption from the cone, but at times this criterion fails completely because of strong winds and possibly other meteorological factors which do not allow the column to mature to its ideal height.

Noises accompanying the eruption from the cone are usually characteristic for each phase of eruption and are shown in Figure 1 by letter symbols, explanation of which are shown in Table 1.

Since the beginning of his observations of the Volcano, Ordoñez [SEGERSTROM and GUTIÉRREZ, 1947] has used a classification of eruptive activity originally based on the characteristic noise accompanying each phase. The noise types listed in Table 1 fit into classification by Ordoñez about as follows: A and B, in the ideal case, accompany the silent phase; C, D, or E, and sometimes H, accompany the tubular phase; and F, G, or H accompany the gaseous phase.

Variations in tidal force and barometric pressure, phenomena that have been suggested as possible factors affecting volcanic activity, are shown above the eruptive characteristics of Figure 1. Barometric pressures were plotted from hourly readings of a fixed aneroid barometer at the Lower Casitas, five km north of the cone. Maximum and minimum values of tide-producing force, computed for the locality of Parícutin Volcano by the U. S. Coast and Geodetic Survey, were plotted and the intervening values sketched. Although a thorough analysis of these data has not yet been made, preliminary study does not seem to show a consistent correlation of the activity of Parícutin Volcano with either barometric pressure or tidal force during the period, September 18 to November 30, 1946.

Activity of the cone--During this period, as shown in Figure 1, the eruption of pyroclastics from the cone was generally erratic, and the amount erupted changed abruptly many times from one extreme to the other. The emission of vapors was great, regardless of the amount of pyroclastics.

The character of the crater on September 18 has been described by SEGERSTROM and GUTIÉRREZ [1947]. On October 22 the form of the crater was that of a simple inverted cone, 140 m deep, with three vents spaced within a radius of 20 m at the bottom. These vents emitted

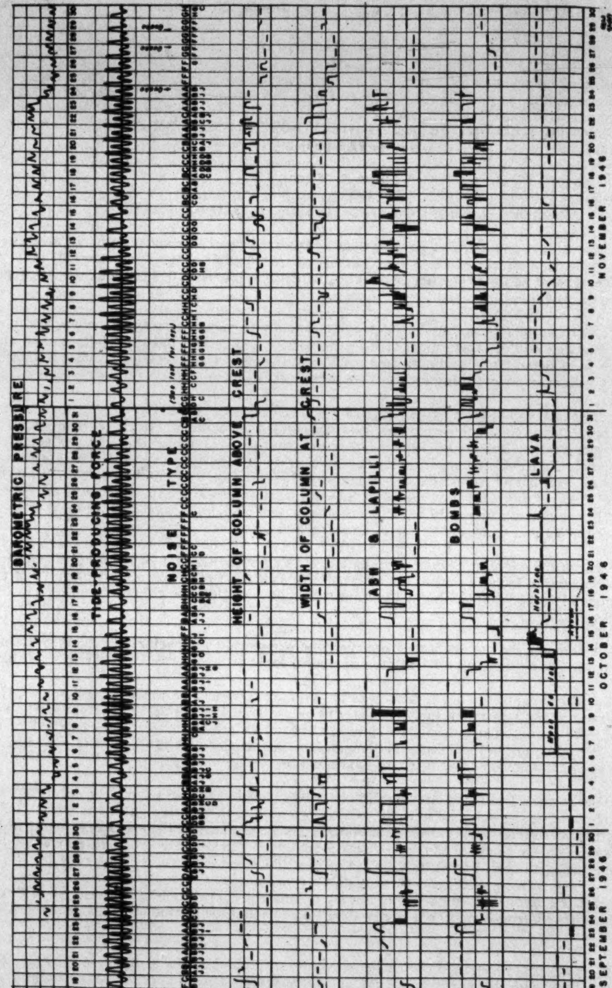

Fig. 1--Eruptive characteristics of Parícutin Volcano from September 18 to November 30, 1946

Table 1--Noise types of Figure 1.

Types	Description
A	Soft surging or swishing noise, barely audible at distances greater than one km
B	Louder and more profound surging noise than A, similar to heavy surf breaking on a shore
C	Thunder-like noise, rolling and reverberating, lasting two to fifteen seconds, often initiated by heavier explosions
D	Noise like that of muffled heavy artillery fire
E	Noise like that of light artillery fire, sharper than D and often producing visible compression waves
F	A steady rushing roar, like the jet emission of steam under very high pressure, continuing uninterrupted for periods ranging from one to thirty minutes
G	Undulating noise of jet emission of steam under high pressure; this type sounds much like a distant fast-traveling railroad train, with the intensity and quality of the noise changing as the train passes irregularities in the terrain
H	Intermittent noise of jet emission of steam, usually harsher in quality than that of F or G, alternating periods of noise and silence range from three to sixty seconds in length, and at times are sufficiently regular in periodicity to resemble the slow chugging of a hard-pulling freight engine
I	Noise like that of a pistol shot, caused by point discharge of electricity in the eruptive column
J	Flat slap noise, caused by falling volcanic bombs, with many bombs falling, the noise resembles the confused beat of horses' hoofs
O	Complete lack of noise for more than five minutes

strong jets of yellowish-white vapors, accompanied by little ash and few bombs. On November 1 the crater was bowl-shaped and only about 30 m in depth. By November 26 a conical crater had formed within the bowl-shaped crater and had extended the total depth to 100 m. At the bottom, multiple jets of vapor issued from incandescent perforations in a rock plug about 15 m in diameter.

The external form of the cone changed little during September 18 to November 30. All portions of the rim grew slightly, and the elevation of the highest point, the east rim, increased from 2750.9 m above sea level on September 16 to 2758.9 m on November 28. Some time during the period November 26-29 occurred a limited collapse of a portion of the V-shaped notch between the cone proper and the southwest segment of the cone that had been shoved outward in March, 1946. It is not known whether this collapse and the associated collapse of the crest of the then defunct Ahuan vent were related to sharp earthquakes felt at Cuzeno, November 24 and 27 and at Angahuan, November 29. Erosional rills, an uncommon feature, were noted on the eastern flank of the cone November 11, and by November 29 many had attained a depth of 30 cm.

Activity of the lava vents--Figure 1 shows the relative rates of lava production from the vents. The Ahuan vent, at the SSW base of the cone, experienced declining activity during the latter part of September and finally ceased about October 18. The Mesa de los Hornitos vent, 100 m from the WSW base of the cone, was the major producing vent during the period of this report. Its rate of lava production was only small to moderate until October 13. From October 13-15 a series of brilliant lava fountains occurred at this vent, building up an arc-shaped spatter cone ten m in height. The conelet, however, was gradually destroyed in the ensuing weeks by the steady flow of lava from the vent area. The strong lava fountaining of October 13-15 coincided with a temporary decrease in the amount of pyroclastics erupted from the cone, and a period of strong lava production November 5-8 coincided with a similar decrease in pyroclastics from the cone.

Activity of the lava flows--The maps of Figures 2 to 4 show the areas covered by lava during September, October, and November. In September (see Fig. 2) the pincer-like flow that partially surrounded Jaratiro Hill was the continuation of an Ahuan vent flow of August that had circled the east base of the main cone and Zapichu. The small flow, one km north of Curinguaro, was the dying movement of another Ahuan vent flow of August. During September three flows locally passed the previous limits of the lava field.

The flows of October (see Fig. 3) were mainly from the Mesa de los Hornitos vent, located on a divide WSW of the main cone. Because of this situation on the divide, the flows from the Mesa de los Hornitos vent took up various initial courses, depending upon which side of the vent mound they spilled over. Whereas the September flow had been southward, the October flows were, first, westward and then northwestward and northward. One flow, following the western edge of the lava field, cut behind and isolated the abandoned Canijuata Observatory.

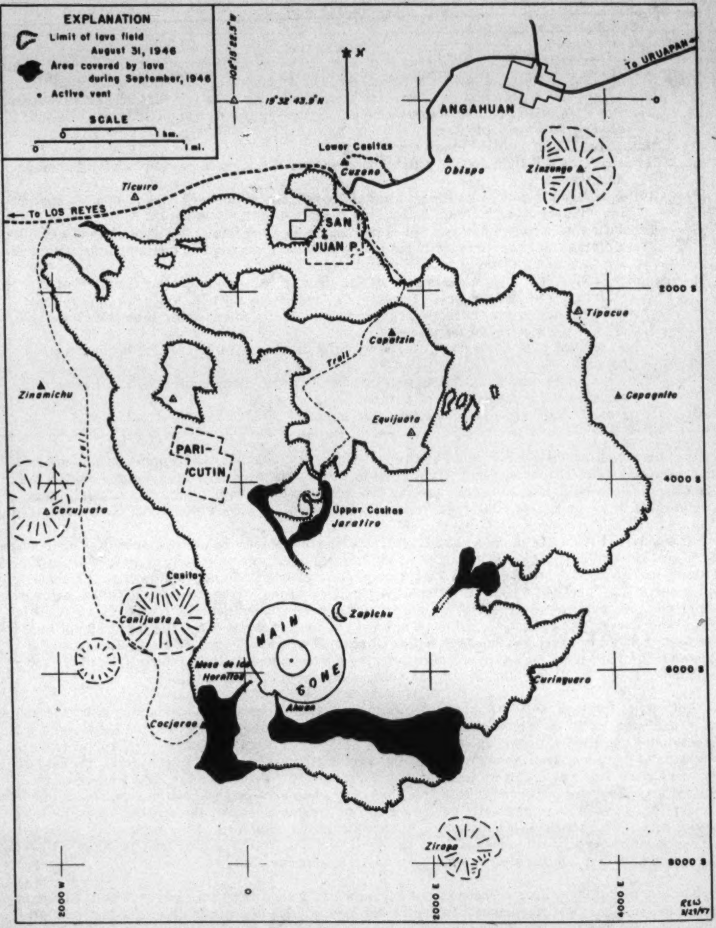
EXPLANATION
Limit of lava field August 31, 1946
Area covered by lava during September, 1946
Active vent
SCALE
0
1 km.
0
1 mi.
102°15'22.5"W
19°32'43.9"N
X
To URUAPAN
ANGAHUAN
Lower Casitas
Cuzeno
Obispo
Zinzongo
Ticuiro
To LOS REYES
SAN JUAN P.
2000 S
Tipacua
Capatzin
Trail
Zinamichu
Cepagnito
Equijuata
PARI-CUTIN
4000 S
Corujuata
Upper Casitas
Jaratiro
Casita
Canijuata
Zapichu
MAIN CONE
Mesa de los Hornitos
Ahuan
6000 S
Curinguaro
Cocjarao
Zirapo
8000 S
2000 W
0
2000 E
4000 E
REW 2/21/47

Fig. 2--Map of Parícutin lavas during September, 1946

During November (see Fig. 4) the still active flows of October continued an additional 800 m northward across the site of the buried village of Parícutin. Another flow, following the western border of the lava field for a distance of two km in the vicinity of Canijuata Hill, overrode and destroyed Canijuata Observatory. During the latter part of November a strong flow followed the west base of the main cone, completely covering a previous flow of November, and at the end of the month was spreading actively northward from the cone.

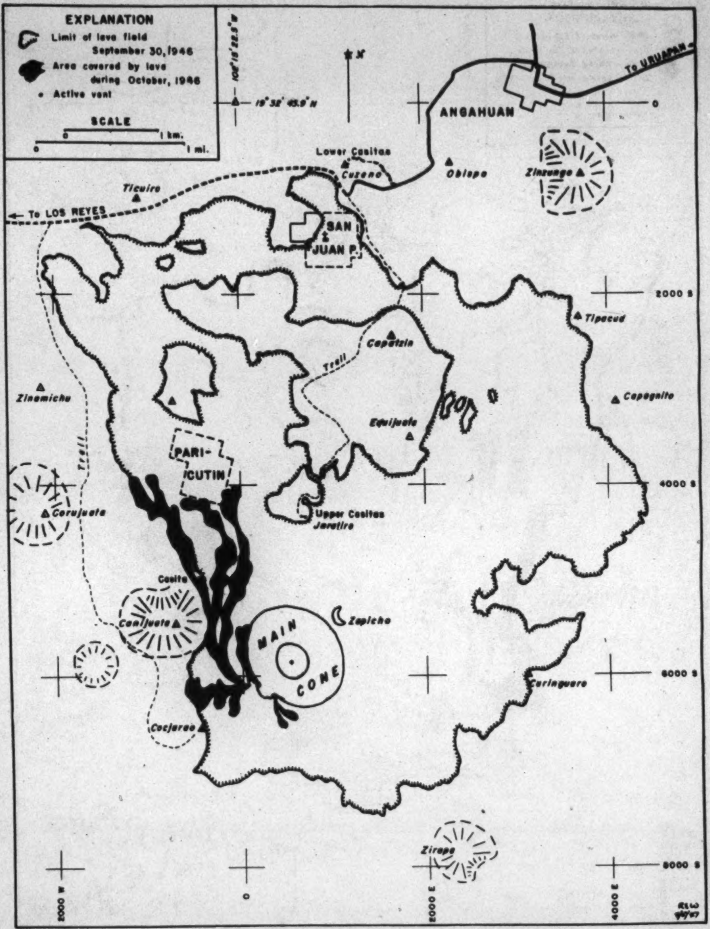
EXPLANATION
Limit of lava field September 30, 1946
Area covered by lava during October, 1946
Active vent
SCALE
0
1 km.
0
1 mi.
102°15'22.5"W
19°32'45.9"N
N
To URUAPAN
ANGAHUAN
0
Lower Casitas
Cuzeno
Obispo
Zinzungo
Ticuiro
To LOS REYES
SAN JUAN P.
2000 S
Tipacud
Capatzin
Trail
Zinamichu
Capagnito
Equijuata
PARI-CUTIN
4000 S
Upper Casitas
Jaratiro
Corujuata
Trail
Casita
Canijuata
Zapicho
MAIN CONE
6000 S
Curinguaro
Cocjarao
Zirapo
8000 S
2000 W
0
2000 E
4000 E

Fig. 3--Map of Parícutin lavas during October, 1946

The surface structure of the flows of the period, September through November, consisted for the most part of rubble and jagged blocks of reddish-black basalt. This structure is typical of most of the previous flows of Parícutin Volcano with the exception of the extensive San Juan flow of 1944 and of local lobes of other flows, surfaces of which are made up of crags and large spines.

The writer is indebted to Kenneth Segerstrom, Richard E. Fuller, Ezequiel Ordoñez, Ariel Hernandez Velasco, Celedonio Gutiérrez and others for much assistance and for providing a picture of the previous activity of the Volcano. He is further indebted to Richard E. Fuller and to the U. S. Coast and Geodetic Survey for the computed data of tide-producing force at Parícutin.

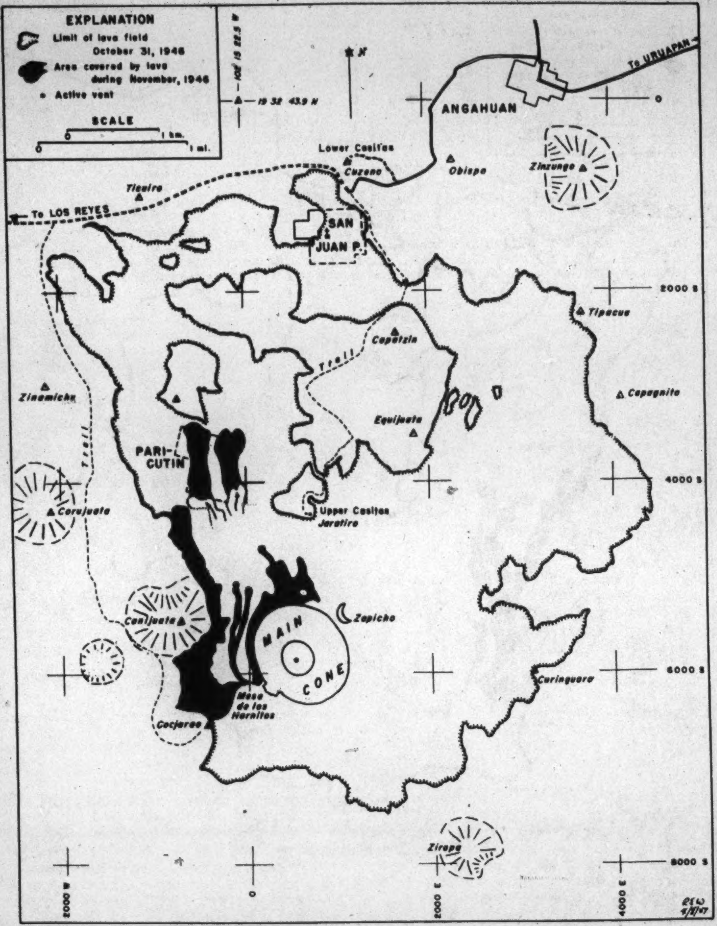
EXPLANATION
Limit of lava field October 31, 1946
Area covered by lava during November, 1946
Active vent
SCALE
0
1 km.
0
1 mi.
102 15 22.5 W
19 32 43.9 N
N
To URUAPAN
ANGAHUAN
0
Lower Casitas
Cuzeno
Obispo
Zinzungo
Ticuiro
To LOS REYES
SAN JUAN P.
2000 S
Tipacua
Capatzin
Trail
Zinamicha
Capacuito
Equijuata
PARI-CUTIN
Trail
4000 S
Corujuata
Upper Casitas
Jaratiro
Canjuata
Zapicho
MAIN CONE
Mesa de los Hornitos
Cocjarao
Curinguaro
6000 S
Zirapa
8000 S
2000 W
0
2000 E
4000 E
REW 4/8/47

Fig. 4--Map of Parícutin lavas during November, 1946

References

SEGERSTROM, KENNETH, and GUTIERREZ, CELEDONIO, Activity of Parícutin Volcano from May 4 to September 18, 1946, Trans. Amer. Geophys. Union, v. 27, pp. 559-566, 1947.

U. S. Geological Survey,
Washington 25, D. C.

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A BASIS FOR UNIFIED FLOOD-CONTROL OPERATION OF RESERVOIR SYSTEMS

C. O. Clark

Abstract--Reservoir operations for passage of flood waters customarily depend upon water levels in the reservoir or upon flows entering the reservoir. Both of these factors are influenced materially by the manner of operation of other reservoirs in the watershed, and by the construction and operation of any dam, levee, or channel improvement in the upstream flood plain. The purpose of this paper is to present a criterion of effective operation which would independent of upstream reservoir operation and which would also be equitably alterable as upstream developments increase or decrease the flood-control capability of the reservoir system. Advance drawdown of pool levels for flood storage and the control of a tributary to keep its flow off the flood peak of a main stream are illustrated. The method is presented as being most useful in reservoir developments principally for power generation, irrigation, and navigation, and secondarily for flood control; and most needed in developments in which only a small amount of reservoir storage capacity is reserved for flood-time use.

The purpose of this paper is to outline a basis for the unified operation of a group of reservoirs as a single system for the accomplishment of a relatively high degree of flood control in proportion to the amount of flood storage available or utilized.

In the operation of a single reservoir, it is quite common to base the operation on the level of the reservoir at the dam, maintaining, either by mechanical or manual means, some relationship between the water level, or the storage volume in the reservoir, and the controlled outflow. This relation may be simple or complex.

In operation of a group of reservoirs, a similar principle can be applied, maintaining a fixed relationship during the period of increasing outflow between storage volume in the group or system of reservoirs and the controlled outflow at the controlling dam. Determining the amount of the storage volume may be a slightly complex task, but the relationship between that volume and the controlled outflow may be ultra simple, merely a fixed linear ratio between the volume and the flow rate, cfs days of volume per cfs of controlled outflow. The dimension of such a ratio is time, in this case, days. Physically, it is the time which would be required to discharge a volume of water equal to the storage at the controlled outflow rate.

The result of such operation is a controlled hydrograph which reaches its maximum flow rate at the time of the end of the storm regardless of whether any water has yet reached the controlling dam or not. Once established, the maximum flow rate is maintained until the flood has been safely passed.

Applicable only to a controlling dam without mechanical limitation upon its capability of discharging flood waters at any desired rate, the method is most applicable where the controlling dam normally maintains a head and a considerable volume of water behind closed crest gates. Such dams are commonly utilized for power, navigation, or multiple purposes, but very seldom for flood control only. Although some storage capacity for flood waters must be available upstream from the dam, it would not necessarily be available in the reservoir of the controlling dam, which could be a power dam with no flood control storage. The storage capacity available may be of the reservoir type retained by dams, or the channel type detained by the obstructionary effect of flow within the channels. If only the latter type of storage capacity were available, operations would have the effect of drawing down the reservoir of the controlling dam. Under these circumstances, the operation would become a practicable method for determining the drawdown in advance of floods upon which some operating reservoirs depend. Calculated operations and the computed results therof will be demonstrated in a single system of reservoirs in three representative possible stages of construction: (1) The initial construction of the downstream controlling dam; (2) the operation of a downstream controlling dam in an advanced stage of river development containing flood and power storage dams and run-of-river power dams; (3) the operation of an upstream storage dam controlling a major tributary.

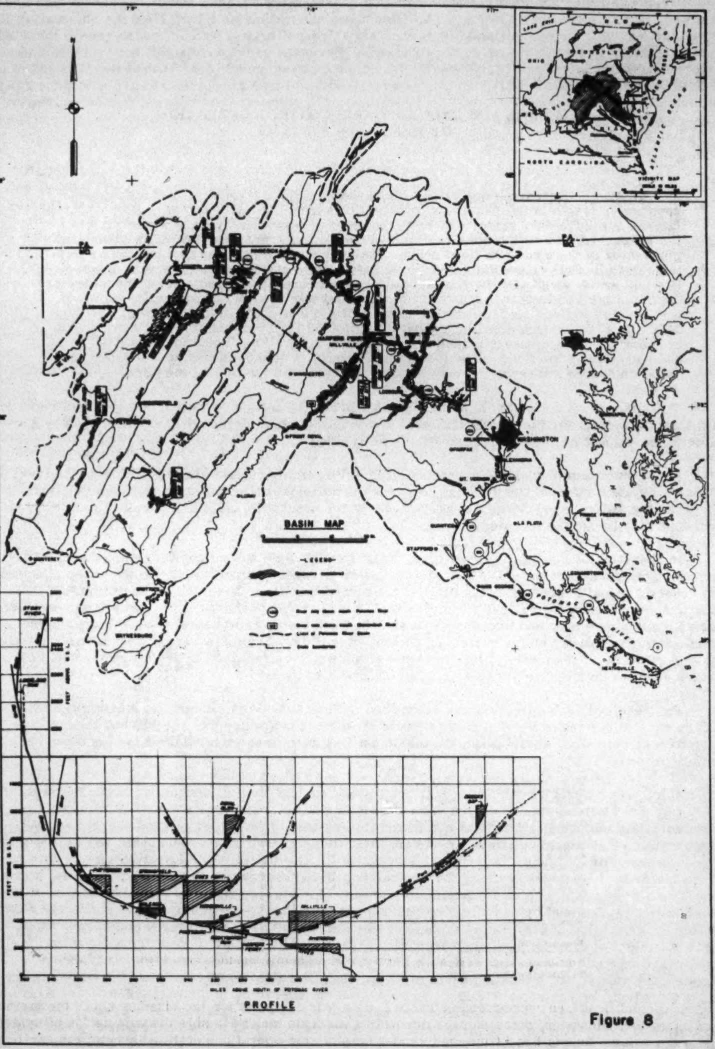
VICINITY MAP
NORTH CAROLINA
ATLANTIC OCEAN
PA.
MD.
HANCOCK
WASHINGTON
POTOMAC RIVER
BASIN MAP
LEGEND
PROFILE
MILES ABOVE MOUTH OF POTOMAC RIVER
FEET ABOVE M.S.L.
Figure 8

Fig. 1--Map and profile of Potomac River watershed

The watershed selected for demonstration is that of the Potomac River, a general map and profile of which are shown in Figure.1. This basin has two major tributaries, the Shenandoah River and the Potomac River, uniting at Harpers Ferry, West Virginia, before flowing across the Piedmont Plateau to the Nation's Capital. The dams discussed are non-existent, but hypothesized at locations which have been considered as feasible for development [see "References" at end of paper, HOUSE DOCUMENT No. 101, 1934].. The overall sizes of dams hypothesized are within the range of possibility at the named sites, but the allocations of storage capacity between two basic types of use, power, and flood control, are selected only to illustrate the points of this paper, and have no particular relationship to any actually proposed plan of development.

To permit consideration of the use of storage capacity anywhere within the watershed, the reservoir system is defined as the natural watercourses, major and minor, and the natural and artificial storage facilities therein. Defined in this comprehensive manner, the system may be considered as a free body upon which the external influences of rainfall and runoff will be the same in any stage of development as in the natural, or pre-development stage. Within such a system, many details, such as flows within individual reservoirs, may be treated as internal influences without effect upon the inflow or outflow from the system which may be regarded as external forces. By so doing, the theory of operation may also be more simply demonstrated. The system is further divided into the major and minor watercourses thereof, in which (1) the major watercourses are those downstream from stream gaging stations from which river stage records may be obtained by radio, telephone, or telegraph under flood conditions, and (2) the minor watercourses are those upstream therefrom to the limits of the watershed. All reservoirs lie within the limits of the major watercourses. In the Potomac River example illustrated, the recording water stage and flow gaging stations of the United States Geological Survey, listed in Table 1, are at or within the limits of the major watercourses. Inflow to the major and minor watercourses during floods is determinable by storage accounting [CLARK, 1944] from the records of these stations (which could be collected by radio or telegraph if the use required it). The inflows and station flows which are used to illustrate the operations presented herein were published [CLARK, 1944] with the applicable principles and constants for their calculation. The storage constants for natural conditions are reproduced in Table 1, as a starting point for the discusssion of the method of operation. However, since storage accounting methods make possible the calculation of system storage volume during flood time, and render feasible the operations outlined herein, the earlier publication is by this statement designated to be an essential part of this presentation.

Table 1--Valley storage capacity of natural watercourses, Potomac River Basin

Gage		Source to gage[a]			To next downstream gage			
Stream	Station	Drainage area	Storage		cfs hrs / cfs	ac ft / cfs	ac ft / cfs-mi	Relative influence-upstream gage
			TC[b]	k[c]				
		sq mi	hr	hr				
North Branch Potomac	Bloomington	287	10	10	6	0.50	.024	0.4
North Branch Potomac	Pinto	122	9	6	4	0.33	.025	0.5
North Branch Potomac	Cumberland	32	4	4	14	1.17	.042	0.5
Potomac River	Paw Paw	547	18	8	9	0.75	.020	0.4
Potomac River	Hancock	294	9	6	14	1.17	.021	0.5
Potomac River	Shepherdstown	1369	30	6	7	0.58	.024	0.5
Potomac River	Point of Rocks	394	10	10	9	0.75	.016	0.5
Potomac River	Washington	653	18	15	. .	. . .	. . .	. .
Savage River	Bloomington	115	11	5	6	0.50	.024	0.4
Georges Creek	Franklin	72	5	5	6	0.50	.025	0.4
Wills Creek	Cumberland	247	8	4	2	0.17	.042	0.5
Patterson Creek	Headsville	216	12	6	14	1.17	.038	0.5
South Branch Potomac	Petersburg	642	15	12	8	0.67	.011	0.5
South Branch Potomac	Springfield	546	24	12	10	0.83	.038	0.5
South Branch South Fork	Moorefield	283	13	9	8	0.67	.013	0.5
Cacapon River	Yellow Springs	306	10	6	15	1.25	.017	0.57
Cacapon River	Great Cacapon	364	16	8	4	0.33	.021	0.4
Conococheague Creek	Fairview	494	30	12	12	1.00	.022	0.5
Antietam Creek	Sharpsburg	281	24	10	7	0.58	.023	0.5
North River	Burketown	375	9	4	5	0.42	.023	0.3
South Fork Shenandoah	Lynnwood	197	6	3	9	0.75	.017	0.5
South Fork Shenandoah	Luray	301	9	4	12	1.00	.020	0.5
South Fork Shenandoah	Front Royal	261	15	6	14	1.17	.022	0.4
Shenandoah River	Millville	442	16	8	7	0.58	.034	0.5
Middle River	Grottoes	360	12	6	3	0.25	.025	0.3
South River	Waynesboro	144	12	6	9	0.75	.026	0.3
North Fork Shenandoah	Strasburg	772	20	7	16	1.33	.022	0.4
Passage Creek	Buckton	87	6	3	18	1.50	.026	0.4
Cedar Creek	Winchester	101	6	2	19	1.58	.023	0.4
Monocacy River	Jug Bridge	817	28	14	12	1.00	.017	0.5
Goose Creek	Leesburg	338	17	8	6	0.50	.012	0.5
Seneca Creek	Dawsonville	101	6	3	4	0.33	.012	0.5

[a] Below other upstream gages only. [b] TC=Time of concentration, translatory storage-factor.
[c] k=Reductive storage-factor.

Efficient control of floods at any point for the maximum benefit at that point calls for the establishment, as early as possible in the flood, of the maximum discharge which cannot be avoided and the minimum flow which can be maintained throughout the flood by the available storage capacity. Thus a uniform rate of flow would be maintained for a considerable length of time, ending with the available storage capacity taxed to the limit but not exceeded. Such control of an idealized flood is shown in Figure 2. Hydrographs of flow at various zone boundaries in the contributing watershed are also shown in Figure 2 and the corresponding volumes represented in mass curve form in Figure 3.

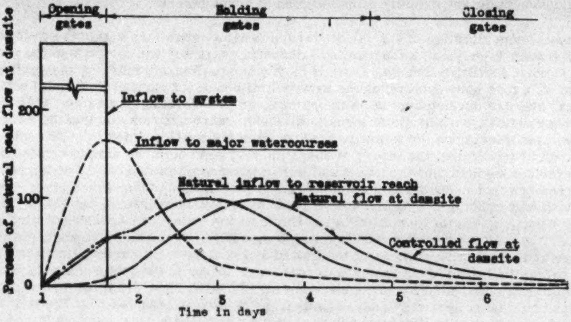

Fig. 2--Typical hydrographs of flow

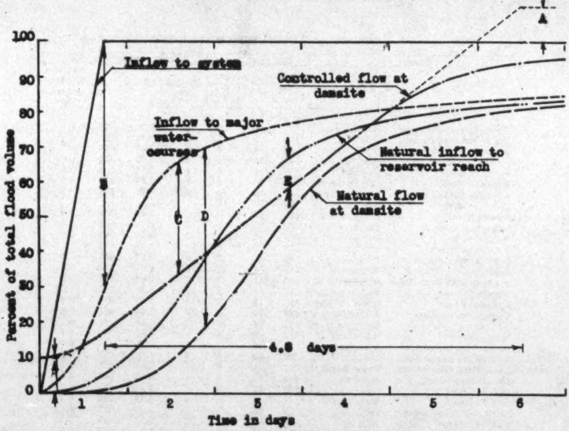

Fig. 3--Typical mass curves of flow volume

Flood control of this calibre can be accomplished in a reservoir system by operation, as suggested herein, only in one particular size and type of flood. This flood will be termed the "design flood" and is the magnitude for which any particular operation will be most effective. In floods of the same duration and type, but of smaller volume, the same percentage of the natural peak flow rate would be passed through the dam, and the same percentages of flood volume would be stored, but a lesser absolute volume would be retained in reservoirs, and the downstream reservoir would not be taxed. In larger floods, the retainable storage capacity of the downstream reservoir would be overtaxed if the operation were continued throughout the flood. However, the fact that the flood was larger than the design flood would be evident and known long before this happened, and revised operations based upon a larger design flood could be immediately undertaken, resulting in a very substantial flood control effectiveness. The overload capability of this type of operation will be mentioned no further for fear of detracting fron the clarity of the presentation of normal operation. This capability will become immediately obvious to one who has familiarized himself with the principle presented, and is a characteristic which recommends the type of operation for consideration where it could be applied.

In further explanation of Figure 2, natural flow at dam site represents the natural flow at Washington, D. C., the hypothesized location of the controlling dam (the so-called Riverbend Site). This hydrograph can be observed and studied from existing records, but cannot occur after completion of the dam. The same hydrograph is presented volumetrically in Figure 3.

Natural inflow tp reservoir reach represents inflow to the reach of river which will be occupied by the controlling dam, a hydrograph which is not observable but which may be computed from the outflow at Washington plus storage changes in the river reach. Such a computing process is easily accomplished either for undeveloped natural conditions or after a reservoir has been built. This flow rate, commonly used in planning operations of a single reservoir, cannot be used as a guide for system reservoir operations, however, since its form can be altered by the operation of any contemplated upstream reservoir. Volumetric representation of this hydrograph in mass curve form is illustrated in Figure 3, as are the volumetric equivalents of all of the hydrographs of Figure 2.

Inflow to major watercourses represents inflow, not to the single controlling reservoir, but to the river channel itself at boundary limits beyond any contemplated reservoirs at the water edge of all main channels and reservoirs. Thus it is similar to inflow to the reservoir in a one reservoir system, but is more nearly inflow to all of the reservoirs and the intermediate channels of major watercourses. This hydrograph can be computed, like reservoir inflow, from the reservoir or natural outflow and the known change of storage upstream. The process of flood storage accounting, an inverse application of flood routing principles [CLARK, 1944], provides the mechanical basis for such computation. In Figure 3 the hydrograph of inflow to major watercourses is represented volumetrically. Ordinate D is the physical volume of stored water in the major watercourses, under natural conditions which can be calculated from a suitable number of staff gage observations along the river, and which is utilized in the flood storage accounting process.

A particular significance of the inflow to major watercourses is the fact that it cannot be influenced by operation of any contemplated reservoirs since it is defined as being upstream from all reservoirs contemplated. Thus it will be the same after development takes place as it has been over the period for which natural flow records have been collected. The nature of this hydrograph is therefore a physical characteristic of the watershed, and serves as a basis for reservoir operation in any stage of river development. The accuracy with which it can be determined is quite satisfactory in either natural or developed conditions, although the needed facilities are likely to be better in the latter case.

Inflow to system is the inflow to the minor watercourses, approximately the inflow to the watershed itself. The existence and the determination of this hydrograph are merely logical extensions of the storage accounting process utilized to determine the inflow to major watercourses as just explained. The accuracy of possible determination of this line is somewhat less than for inflow to major watercourses, but is nevertheless well within the practical limits of good flood control needs.

Remaining for explanation is the controlled flow at the dam site which is the flow released by gate operation at the controlling dam of the contemplated system of reservoirs. The line illustrated embodies the requirements of efficient control; that is, (1) an opening period establishing, (2) at an early time, (3) a discharge which is nearly the maximum which cannot be avoided, and (4) the minimum which can assuredly be maintained throughout the flood by the available storage capacity.

The retainable storage capacity of the reservoir system available at the beginning of the flood is represented in Figure 3 by ordinate A, the detainable storage capacity of the reservoir system (major watercourses only) is represented by ordinate C. (Definitions of retainable and detainable storage follow.)

For selection of a criterion for gate opening, inflow to system is chosen as the primary index and inflow to major watercourses is developed as a check index. The gates will be opened in relationship to inflow to minor watercourses, which will indicate a maximum earlier than any other of the flow hydrographs which have been discussed. A satisfactory and simple relationship for this purpose is to open the gates in such a manner as to provide a discharge rate capable of discharging all water stored upstream in a specified period of time, as for example of Figure 3, in 4.8 days. The water stored upstream is the sum of the storage in major watercourses (ordinates A plus C in Figure 3) plus the storage in minor watercourses (ordinate B). The flow rates from gates opened in this manner can be computed for a simple, typical type of hydrograph. For the hydrograph of Figure 2, the maximum discharges according to this criterion are shown in Figure 4a, "Operation based upon inflow to system."

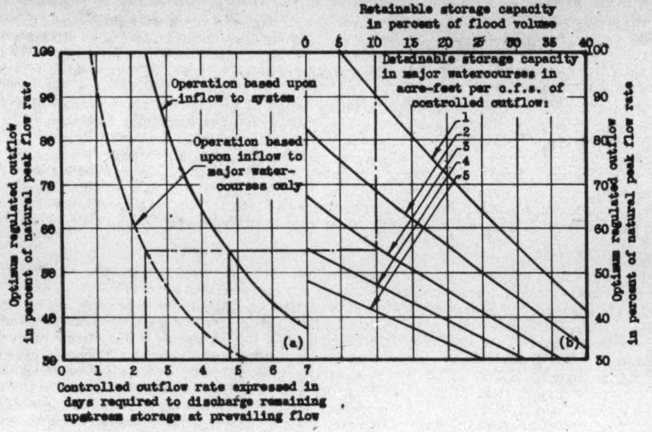

Fig. 4--Optimum flow rates for available storage capacity

The maximum amount of storage capacity required simultaneously in the reservoir system for flood operations conducted in this manner has been computed and is shown in Figure 4b. The storage capacity required is shown as that in the major watercourses only, since it is here that it can be determined contemporaneously during a flood and here that it may be subject to modification by reservoir development.

The storage capacity of the reservoir system can be treated as a single quantity equal to the sum of the capacities of individual reservoirs, provided the individual capacities are small enough and their use such that the storage capacity of each reservoir can be filled and retained until the lower reservoir reaches its maximum level. (Storage capacity in excess of these amounts must be discounted in computing system totals upon which operations are planned. The author would hesitate to count retainable storage capacity of upstream reservoirs in excess of 40 per cent of the design flood volume from above each reservoir.)

What is the storage capacity of a reservoir system? To be equally applicable to all of the stages of river development, the answer to this question must be broad enough to include and evaluate:

(a) The slack water storage capacity of large reservoirs between the minimum and maximum elevations of level pools both of which are below the upper level at which discharge from the dam can be prevented.

(b) The backwater storage capacity between a level pool at the maximum elevation at the dam and the profile of the river for the prevailing flow rate through the reservoir.

(c) Surcharge storage capacity above the level of the crest of free spillway or the top of crest gates in closed position, that is, above the level at which discharge from the dam can be prevented.

(d) Storage capacity in retardation basins above the level of orifice outlets in fixed open position.

(e) Valley storage in undeveloped reaches of river.

Although item (a) is the most easily understood form of flood storage capacity, it is likely to be a small part of the total storage capacity in a reservoir system. If a planner were to imagine it to be the only storage of importance, he might easily be deluded into thinking he had planned a reservoir development which increased the river's storage capacity, when in fact he had only converted some portion of storage capacity of type (e) to capacity of type (a).

The principal difference between storage of type (a) and the others listed above is in the capacity to retain water once stored. This difference is a basis for definition. Storage of type (a) can be confined in the reservoir system as long as desired; it is, therefore, termed retainable storage capacity. Storage of types (b) to (e) is useful while it lasts. However, since the detention of the volume depends upon the existence of a rate of flow of water, these volumes can be confined in given reservoirs or reaches of river only as long as the necessary stream flow continues, and the magnitude of the storage volume varies with the magnitude of the flow rate. Thus this storage can be detained until flow subsides but it cannot be retained indefinitely. It is, therefore, termed detainable storage capacity.

In general, retainable storage capacity is of fixed magnitude (expressable in units of fixed volume as acre feet or cfs days) regardless of the magnitude of flood flows. Detainable storage capacity varies with the magnitude of the flood. In many natural river reaches storage capacity of type (e) is directly proportional to the flow of the stream. Types (b) to (d) are assumed to vary similarly in the discussion which follows. While this is over-simplication of usual fact, a proportion based upon conditions in the anticipated design flood usually will be conservative for smaller flows.

How can the total system storage capacity of the detainable type be expressed? If the flow were absolutely steady, as if resulting from a continuous steady rate of rainfall (or more exactly, runoff) over the entire area, this could easily be done. Under this condition, the flows at all points in the system would all be proportional to drainage area, the storage in each reach of river could be stated in acre feet per cfs, and the total in the river system in acre feet per cfs of flow at the outlet point. This relationship could be true in flood time only for steady flow, a condition which cannot exist but is approximated in any reach when the inflow and outflow are equal. Within the major watercourses this time is just after the middle of the second day in Figures 2 and 3. The relationship is more exact, but less conservative, in floods of long duration. In floods of short duration, flows intermediate between inflow and outflow are materially larger and the storage quantity is larger than if the hypothesized steady flow prevailed. In all of the flood period prior to the time at which major watercourse inflow decreases to a value less than system outflow, storage capacity of detainable type is dependable in amounts somewhat exceeding ratios computed from steady flow. After this time, but under conditions which the author finds to be less critical, detainable storage capacity declines to insignificant proportions as flood flows recede.

Table 2 shows the values of detainable storage capacity which have been computed for the natural condition of the stream to which Figures 2 and 3 apply. These values total 3.06 acre feet of storage per cfs of steady flow at Washington. Table 3 shows the recomputed values of detainable storage capacity in the first stage of river development as altered by reservoir construction. In this stage, valley storage capacity of the reach from above Point of Rocks to Washington would be eliminated by the construction of a dam and reservoir which would have capacity of 1.0 acre feet per cfs (0.11 + 0.89) in backwater and surcharge storage of types (b) and (c). Evaluated in a design flood of as large magnitude as it is deemed reasonable to expect (taken equivalent to 5.0 inches of runoff in 18 hours or 3,100,000 acre feet from a watershed of 11,560 square miles), the natural valley storage in the reach occupied by the initial reservoir would be 10,763 acre feet in a flow of one cfs per square mile, which is 0.93 acre feet per cfs (or about 490,000 acre feet at the maximum average flow of 530,000 cfs for the design flood in that reach). In case that there is also provided storage capacity of type (a) for 310,000 acre feet in this new reservoir, or ten per cent of the flood volume in the predicated design flood, we have in the first stage of development a system containing retainable storage capacity of ten per cent of the flood volume plus detainable storage capacity of 3.12 acre feet per cfs. As the arrowed line on Figure 4 shows, the developed storage is enough to permit reduction of floods to 55 per cent of natural peak flow rate, as illustrated by Figure 2. These storage values compare with a natural state of development of 3.06 acre feet per cfs. Actually, then, there would be but little more (about 11 per cent of flood volume) storage capacity than in the natural stage of the river. However, and this is very important, the first stage of development provides a mechanical means of flow control which makes reductions possible which were not possible in the natural stage for lack of such flow controls (this may be more apparent by further reference to Figure 4b. On this Figure the natural stage storage capacity would be represented as 3.06 acre feet per cfs of flow and zero retainable storage capacity. Interesting to note from this Figure is the fact that naturally available storage capacity of the river is enough to

Table 3--Valley storage in the major watercourses of the Potomac River

Stream	Gaging station	Drainage area	Valley storage	
			Per cfs	For one cfs/sq mi
		sq mi	ac ft	ac ft
Savage River	Bloomington	115	0.20	23
North Branch Potomac	Bloomington	287	0.20	57
Georges Creek	Franklin	72	0.37[a]	27
North Branch Potomac	Pinto	596	0.47	280
Wills Creek	Cumberland	247	0.09	22
North Branch Potomac	Cumberland	875	0.75	656
Patterson Creek	Headsville	216	1.75[a]	378
South Branch Potomac	Petersburg	642	0.33	212
South Fork South Branch	Moorefield	283	0.33	93
South Branch Potomac	Springfield	1,471	0.75	1,103
Potomac River	Paw Paw	3,109	0.80	2,487
Cacapon River	Yellow Spring	306	1.20[a]	367
Cacapon River	Great Cacapon	677	0.76	515
Potomac River	Hancock	4,073	0.97	3,951
Conococheague Creek	Fairview	494	0.50	247
Patterson Creek	Headsville	216	1.88[a]	406
Potomac River	Shepherdstown	5,936	0.51	3,027
Total above Shepherdstown		5,936	2.33	13,851
North River	Burkstown	375	0.10	38
South Fork Shenandoah	Lynnwood	1,076	0.67	721
South Fork Shenandoah	Luray	1,377	0.88	1,212
South Fork Shenandoah	Front Royal	1,638	0.97	1,589
Shenandoah River	Millville	3,040	0.75	2,280
Middle River	Grottoes	360	0.08	29
South River	Waynesboro	144	0.22	32
North Fork Shenandoah	Cootes Store	215	0.33	71
North Fork Shenandoah	Strasburg	772	1.03	795
Cedar Creek	Winchester	101	0.63	64
Passage Creek	Buckton	87	5.33[a]	464
Total above Millville		3,040	2.40	7,295
Potomac River	Shepherdstown	5,936	0.29	1,721
Shenandoah River	Millville	3,040	0.29	882
Monocacy River	Jug Bridge	817	0.50	408
Antietem Creek	Sharpsburg	281	0.29	81
Passage Creek	Buckton	87	0.66[a]	57
Potomac River	Point of Rocks	9,651	0.66	6,370
Goose Creek	Leesburg	338	0.90[a]	304
Potomac River	Washington	11,560	0.38	4,393
Total above Washington but below Shepherdstown and Millville		~~11,560~~	~~1.29~~	14,216
Total above Washington		11,560	3.06	35,362

[a] Flow at this station used as index of flow from other ungaged areas in vicinity on a drainage-area proportion.

Table 3--Detainable storage capacity in the Potomac River as modified in first stage of river development

Stream	Gaging station	Drainage area	Valley storage	
			Per cfs	For one cfs/sq mi
		sq mi	ac ft	ac ft
Total above Shepherdstown		5936	2.33	13,851[d]
Total above Millville		3040	2.40	7295[d]
Potomac River	Shepherdstown	5936	0.29	1721
Shenandoah River	Millville	3040	0.29	882
Monocacy River	Jug Bridge	817	0.50	408
Antietam Creek	Sherpsburg	281	0.29	81
Passage Creek	Buckton	87	0.66[a]	57
Goose Creek	Leesburg	338	0.90[a]	304
Total above first reservoir		10,499		24,599
Reservoir surcharge		11,560	.89[b]	10,288
Backwater storage		11,560	.11c	1272
Total above Washington		11,560	3.12	36,159

[a] Flow at this station used as an index for flow from other ungaged areas.

[b] 400,000 acre feet for flow of 450,000 cfs.

[c] 50,000 acre feet for flow of 450,000 cfs.

[d] From Table 2.

hold the floods to 65 per cent of the peak flows which occur. However, for lack of a device capable of discharging water at the desired time, prior to middle of second day in Figure 1, the flow for which there is storage capacity cannot be realized).

Thus, strange as it may at first appear, the initial requirement for flood control is for discharge capacity in gates of large size and for an initially available supply of stored water from which to release these large rates during the period when inflow to the reservoir is less than the desired outflow.

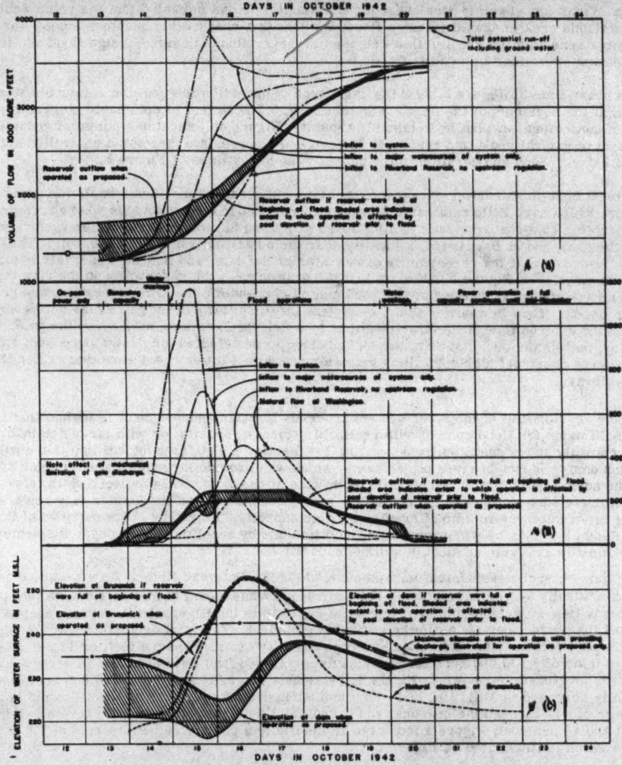

Fig. 5--Main stream control by initial development

An operation of the initial project in a flood like that of October 1942 is illustrated in Figure 5. In this Figure, outflow rates and operation are shown, both for 450,000 acre feet of initially available retainable storage capacity (light line), and in event that retainable capacity were full when the flood started (heavy line). The 450,000 acre feet shown as available for use is about 15 per cent of the design flood (3,100,000 acre feet). Figure 4b indicates for 15 per cent retainable and 3.1 acre feet per cfs detainable storage that reduction to 50 per cent of natural peak discharge is feasible, and Figure 4b indicates that such an outflow would result from a contolled outflow rate of 5.2 days, that is, by maintaining a flow rate from the dam capable of discharging all flood waters in upstream storage in 5.2 days.

In this operation, the discharge at Riverbend Dam, the hypothesized controlling dam near Washington, D. C., is maintained at a rate of flow which if continued would pass the flood flow stored upstream from the dam in 5.2 days. The maximum rate so established, 200,000 cfs, is continued until the controlling reservoir reaches its maximum level and decreased gradually there after. (Although not illustrated herein, the adequacy of the rate so established can be checked during the opening period by comparing the outflow with a similar flow which would pass storage in major watercourses only in 2.7 days. Figure 4a indicates that the maximum flow value so computed from storage in major watercourses would be the same as that computed from system inflow in a flood of design magnitude. Examination of larger and smaller floods indicated that the value would be larger in floods greater than the design flood, and that this check value becomes a good warning of the possible necessity for greater flow relaases in larger floods than the design flood and is a good check on operations in smaller floods.)

The heavy lines in Figure 5 show the same type of operation in event the retainable storage were full at the beginning of the flood. For this case, 3.1 acre feet of detainable storage capacity per cfs of controlled flow, but no retainable capacity, Figure 4b indicates a potential reduction to 65 per cent of natural peak, and Figure 4a indicates as appropriate therefor a controlled outflow rate of 3.9 days. Such an operation is indicated by the heavy lines of Figure 5.

As mentioned in an earlier paragraph, this type of operation provides a basis for drawdown of reservoirs which have little retainable storage capacity under circumstances where such drawdown is practicable. This characteristic is illustrated in Figure 5c, which shows water surface elevations at the dam, and at Brunswick, a locality near the upstream end of the reservoir. These elevations show both that the reservoir is drawn down at the dam, and that the reservoir is far from level. Examination of Figure 2 will show that the drawdown of the reservoir and the rise into surcharge storage are both functions of the flood magnitude, and for the same operation, are greater in bigger floods. Thus in a larger flood, even very large spillway crest gates may not be able to discharge the desired flow at the low elevations to which the drawdown may carry the pool. This is a factor, both in the decision as to the size of flood to be selected for design purposes, and in the decision to construct higher spillway gates for use with a lower crest elevation rather than a longer spillway.

As the development of the river system proceeds for many purposes, it is logical that there will be built dams for flood control with retainable storage capacity, or with large detainable storage capacity above small spillways or low-level outlets. It is also logical that there will be navigation dams or run-of-river power dams, which will provide large permanent bodies of water within the normal flood channels and little or no rise at the dams in high water. Both types of dams eliminate some of the natural detainable storage capacity, and the former may replace the loss with an even larger volume of created storage capacity. Likewise, large portions of the natural flood plain may be withdrawn from floodtime use by erection of levee systems, which also reduce naturally available detainable storage capacity.

In Figure 6, such development is hypothesized for the Potomac River. As a result, it is assumed, naturally available retainable storage capacity has been reduced to 1.4 acre feet per cfs of steady flow at Washington, and surcharge capacity in the Riverbend Reservoir near Washington is 1.0 acre feet per cfs as in the initial development. The total detainable storage capacity is now 2.4 acre feet per cfs. Retainable storage capacity of 555,000 acre feet, or 18 per cent of the design flood of 3,100,000 acre feet previously mentioned, has been provided in several upstream reservoirs. (At locations shown in Figure 1, retainable storage capacity of 555,000 acre feet would be normally reserved in Millville, Edes Fort and Springfield Reservoirs and more would become available in others through the seasonal and operational depletion of power pool levels.) For 2.4 acre feet and 18 per cent, Figure 4 indicates as desirable a controlled outflow rate of 5.0 days, an operation which is illustrated on Figure 6.

Although there is very little difference in the capability of the reservoir systems illustrated in Figures 5 and 6, or in the resulting controlled hydrograph, there is a big difference in the inflow to the Riverbend Reservoir. This illustrates the fact that inflow to the reservoir itself is not a good criterion for operation in a developing river system.

The details of distribution of storage capacity and stored volumes are shown near the center of Figure 6, plotted with respect to a straight line. In the mass curve above, these storage values are represented in total values with respect to the curved line of regulated flow at site. Ordinates measured downward (a) represent retainable storage capacity available for use, and measured upward (b) represent volumes of water stored as detained storage in the system.

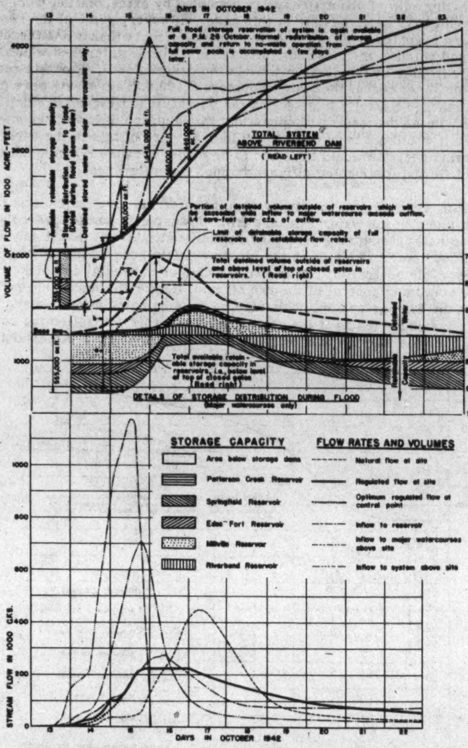

Fig. 6--Main stream control by advanced development; case A

The flood illustrated is 16 per cent smaller than the design flood. Principally for that reason, an amount of storage capacity equal to 16 per cent of the retainable capacity has not been used. Most of the unused portion of storage capacity is in unused surcharge capacity at Riverbend (Figure 6, center, shows only 80,000 acre feet utilized, although 220,000 acre feet of surcharge would have been usable at 220,000 cfs, and retainable capacity at Springfield Reservoir above which runoff was insufficient to fill the capacity).

Any system of multiple-purpose reservoirs may be found at some times to have more storage capacity available than that which is exclusively reserved for floodtime use. In a power dam or group of dams this may come about through the systematic or necessary drawdown over a period of several months to supply water and power needs. When such storage is available, it is usually to the advantage of everyone concerned to make the maximum use of the storage capacity available, regardless of the reason or purpose which makes it available. In Figure 7 is shown the operation which might be appropriate to the same system of reservoirs to which Figure 6 applied in case that reservoir system were drawn down considerably. In the illustration of Figure 7, initially available retainable storage capacity is 1,280,000 acre feet, or over 40 per cent of the volume of the anticipated design flood. For such a value, and the 2.4 acre feet per cfs of detainable storage characteristic of this stage of development, reduction to something less than 30 per cent of natural peak flow by an operating rate of about 10 days is indicated by extrapolation from Figure 4, and such an operation would have been feasible in this case. However, some of the reservoirs, Springfield and Millville, are graphically shown to have capacity of more than two watershed-inches (40 per cent of the design flood volume, the maximum amount on a single watershed which the author deems likely to be assuredly fillable by the desired time in the design flood). For this reason, only 1,000,000 acre feet (or 32 per cent of the design volume of 2,100,000 acre feet).were considered to be available retainable storage capacity in selecting the operation for Figure 7 which is shown as a 6.8-day release rate. In the demonstrated operation, this appears to have been an unduly conservative evaluation, but it would not have been possible to be sure of this in the early portion of the flood when the operating decision would have had to be made, because it would not necessarily be true in other types of floods, distributed differently upon the watershed.

Each operable dam within the reservoir system may operate as a controlling dam upon its own watershed without influencing the water releases from downstream dams adversely by that operation, provided it terminates its storing period by retaining all storage that it can in that flood until the lowest dam in the system is ready to empty (or may safely receive the flow released from upstream). Also, a reservoir controlling one of two tributaries uniting at a damage center may be operated, not for the maximum control of its own stream, but for the maximum reduction of the combined streams at the damage center. This may be done by calculating flows at the damage center on the combined tributaries as if the controlling reservoir controlled the combined flow, and releasing water from the storage dam on the off-stream tributary at times and rates which do

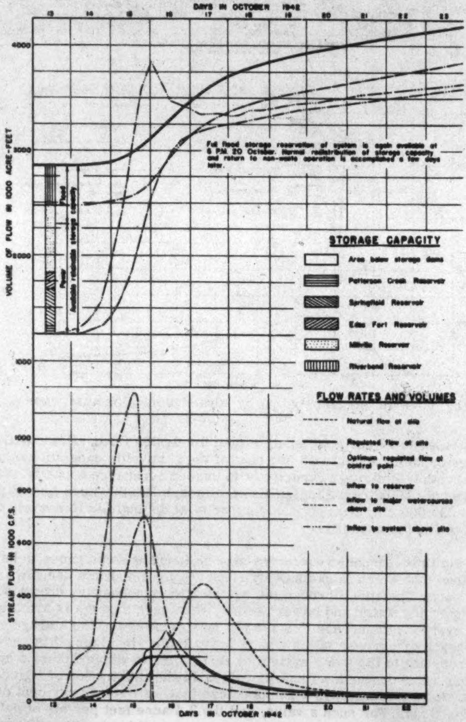

Fig. 7--Main stream control by advanced development; case B not exceed the flow rates in the combined streams which would be necessary even if the combined flow were entirely controllable. Such an operation, while not quite perfect, is nevertheless a very suitable criterion for conserving the off-stream storage by high releases in the early part of the flood, but nevertheless avoiding most of the hazards of continuing the release to the point where it might be damaging.

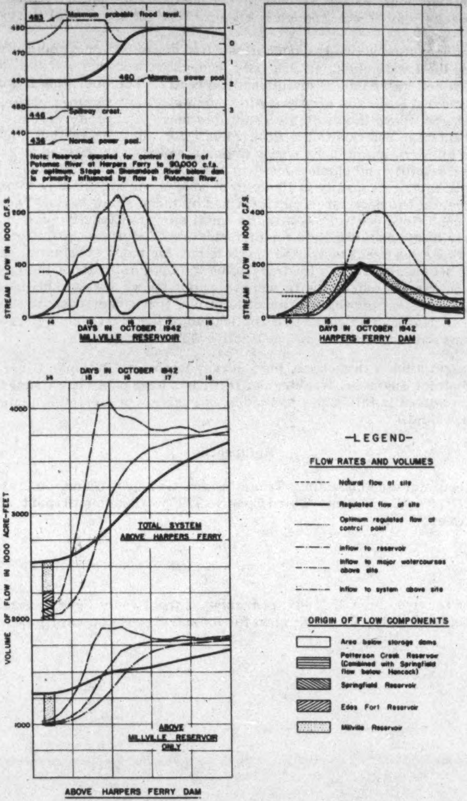

Fig. 8--Off stream control; case A

An operation of this character is illustrated by Figure 8. In the Potomac River watershed, two major streams, the Shenandoah River and the main stream of the Potomac meet at Harpers Ferry and produce damage from there to Washington. The hypothesized dam, Millville, on the Shenandoah, is located so close to the junction of the streams, that there is no point to using the dam to maintain minimum flows on the short remaining portion of its own channel, but there is excellent opportunity for using it to maintain minimum flows on the combined stream. The Harpers Ferry Dam, indicated by one of the drawings of Figure 8, would be only a small run-of-river dam below the junction, but wholly without potential ability to alter flows passing through it

The operation of Figure 8 is for the same period and status of river development as was illustrated by Figure 6. It shows the manner in which a single reservoir within a system may be operated simultaneously with and independently of a downstream reservoir without detriment to either. In the operation shown, the controlled flow desirable (optimum) at Harpers Ferry is computed based upon a 5.0 day release of storage volumes in the total system above Harpers Ferry. Water to supply this optimum rate is released from the operable storage dam at Millville, thus conserving its capacity almost well enough to keep its flow off the peak at Harpers Ferry.

The method of operation which has been illustrated depends a great deal upon adequate communications during the flood period, as it is only through such means that the continuous inventory of upstream stored water can be maintained currently. The operating flexibility of spillway crest gates of considerable size is necessary for completely satisfactory usage. The method has its greatest advantages where the available retainable storage capacity is less than any operator would desire, and small in relation to the flood volume for which protection would be desired. It is, thus, adaptable to operation of dams whose major elements are devoted to navigation or power production, where flexibility and communications are normally good, and where assuredly available retainable flood storage capacity is likely to be at a premium. It is recommended to those whose operating system has been largely determined by factors now beyond remedy, but where it is desired to do a good flood control job with the small storage capacity available. It ought not be used too extensively in the planning field for the selection of storage capacities to be reserved for flood use, except where the benefits are too small to pay for more substantial capacity. This is believed to be true because there is a tendency to be too optimistic about the facility with which any operation can be carried out. Even though this paper shows a way to utilize small storage capacity effectively, it does not prove, or attempt to prove, that larger capacities are not desirable where they can be obtained. It is hoped that application of the principles will enable and encourage operators of existing dams to provide more effective flow control.

(Since the presentation of this paper, the "Survey Report on Potomac River and its Tributaries", prepared by the District Engineer, Washington, D. C. has been publicly released. Operations similar to those presented in this paper are more extensively presented in plates 50 to 54 and in Appendix B, thereof.--Ed.)

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PROPERTIES OF PARTICLES OF SNOW AND THE ELECTRICAL EFFECTS THEY PRODUCE IN STORMS

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Abstract--This paper describes studies of the physical properties of snow crystals, with particular reference to the electrical characteristics measured during snow storms. Two types of atmospheric electricity were found to occur during storms. These have been related to specific forms of snow crystals and other properties which can be observed at ground stations. Measurement of falling velocity, quantity and sign of electric charge, mass, range in quiet air, variety of crystal forms, and other properties of single crystals are given. The fragmentation which results when snow crystals hit a solid at high velocity is described and illustrated with photomicrographs. The frictional electricity produced when crystals are broken as they hit a metal surface when compared to the charge carried by falling crystals is found to be more than a hundred times greater in some instances. Unusual amounts of atmospheric electricity recorded in fair weather are described and shown to be related to the passage of frontal systems and other meteorological phenomena. A method is described for preparing snow-crystal replicas and for measuring the size and distribution of cloud particles.

During the winter of 1943-44 a research program was undertaken at Schenectady, New York, and at the Mt. Washington Observatory in New Hampshire which had as its objective a better understanding of some of the fundamental aspects of precipitation static. Work was carried out under the supervision of Irving Langmuir of this Laboratory, who was requested to do so by the War Department. This program of study and experimentation was part of a larger project concerned with the elimination of precipitation static on aircraft carried out by the Army Radio Laboratory at Wright Field under E. L. Cleveland.

Precipitation static develops on an aircraft when it flies through regions of the atmosphere containing quantities of snow, rain, sand, or other particulate matter. Under certain conditions the ship charges up to such a high electrical potential that it goes into corona and a brush discharge of the "St. Elmo's Fire" type appears on various portions of the plane. The resultant static from this electrical discharge increases the noise level on radio transmitters and receivers to such an extent that all communication facilities, such as ship-to-ground, direction-beam, and even interplane communication become inoperative.

Other groups were charged with various related phases of this problem. The writer was asked to make a study of some of the fundamental physical properties of snow crystals and snow storms, with particular emphasis placed on their electrical properties.

Besides reporting the specific results which were obtained in this study, a description will also be given of certain developments which are inevitable by-products of a study of this kind.

To carry out this project some thought was given to the regions where natural snow was common enough to provide the raw material for experimental studies. Langmuir proposed that the summit of Mt. Washington in New Hampshire should be considered as one of the study sites. This mountain is world famous as having "the worst weather in the world," due to a combination of high wind velocity (often over 100 mph; highest recorded 231 mph), low temperature (often - 20°F; lowest recorded - 46°F), severe icing clouds, and heavy snowfall. While other regions experience greater cold or heavier snowfall, no other accessible place is known to experience the combinations of severe weather which occur on this mountain. In addition to these conditions, Mt. Washington has an excellent Observatory in cooperation with a regular station of the United States Weather Bureau. The men working at the Observatory have the training and enthusiasm which are prime requisites for conducting successful scientific observations under the rigorous conditions imposed by the elements. A photo of the Observatory and surroundings is given in Figure 1.

Fig. 1--Mt. Washington Observatory, New Hampshire

After making the necessary arrangements to carry out studies at the Observatory, it was decided in addition to establish a snow-study laboratory on top of the Research Laboratory building at Schenectady, New York, and at a site at about the same elevation at the edge of the Rotterdam Hills above Schenectady.

The necessary equipment, including a 20-kv supply, two sets of electrodes, an amplifier, and recorder, for Mt. Washington s studies was constructed and installed at the Observatory by the middle of October. A heavy snow storm at that time closed the road until June, 1944. Meanwhile the installation at Schenectady was made ready and initial studies were carried out during a heavy snowfall on November 22, 1943.

The snow laboratory at Schenectady was located on top of the main building of the Research Laboratory at a height above ground level of about 110 feet (330 feet above sea level). In this situation the Laboratory was the highest spot for a distance of several miles. The prevailing winds during the winter time are between west, north, and northeast, the more extensive storms coming from the last direction. Snow showers more frequently come from the northwest. Very little industrial pollution of the air is possible from the directions mentioned above, because the wooded Rotterdam and Glenville hills bordering the Mohawk Valley are in the upwind direction. Air from the east to the south and southwest, particularly the latter, would tend to have the maximum pollution. No effects related to air pollution were observed during the study.

The building housing the snow-study instruments was surmounted by a galvanized chimney utilized for admitting snow crystals into a study chamber at its base. The general layout is shown in Figure 2. Suitable amplifying and recording instruments, a high-voltage source, atmospheric electricity collectors, a photomicrographic outfit, gold leaf electroscope, and other facilities were included in the snow laboratory. These will be described in greater detail as the various results of the research and experiments are given.

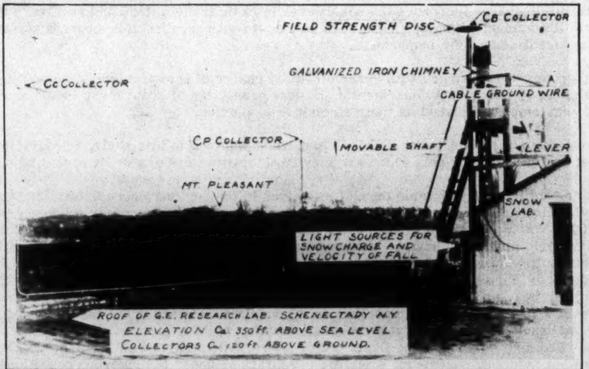

FIELD STRENGTH DISC
CB COLLECTOR
GALVANIZED IRON CHIMNEY
CC COLLECTOR
CABLE GROUND WIRE
CP COLLECTOR
MOVABLE SHAFT
LEVER
MT PLEASANT
SNOW LAB.
LIGHT SOURCES FOR SNOW CHARGE AND VELOCITY OF FALL
ROOF OF G.E. RESEARCH LAB SCHENECTADY N.Y
ELEVATION Ca 350 ft. ABOVE SEA LEVEL
COLLECTORS Ca 120 ft ABOVE GROUND.

Fig. 2--General layout of snow-study instruments at the snow laboratory, Schenectady, New York

Sufficient facilities for basic studies were provided at the writer's home on the edge of the Rotterdam Hills. This station is located 2.1 miles west-northwest of the Research Laboratory at an elevation of 260 feet above sea level. This added facility made it possible to continue observations at night during storm periods.

Classification of precipitation forms which occur in snow storms--Shortly after starting work at the snow laboratory at Schenectady and on Mt. Washington, it became apparent that a descriptive chart was needed to depict the forms of snow crystals occurring at a specific time in a particular storm.

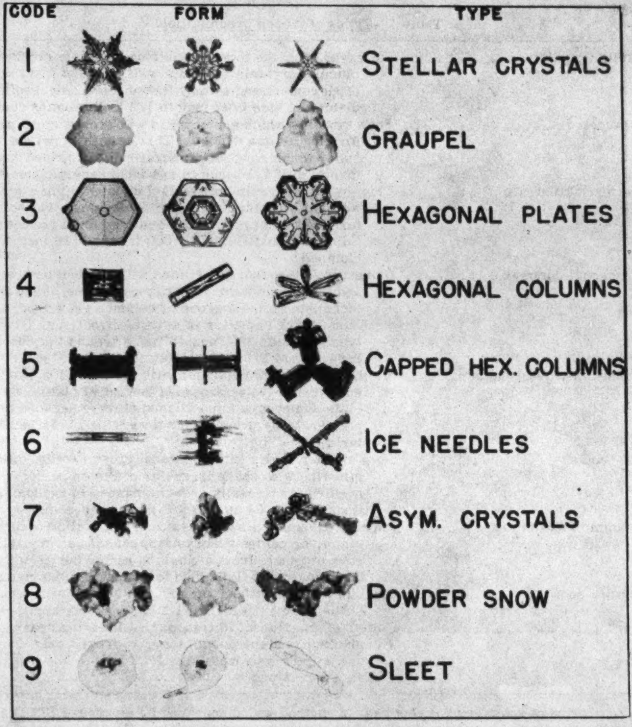


Fig. 3--Types of frozen precipitation

Previous workers in the field [see "References" at end of paper, BENTLEY and HUMPHREYS, 1931; DOBROWOLSKI, 1923; HELLMANN, 1893; NAKAYA and SEKIDO, 1935] have worked out systems of this kind, but a survey of the various proposed classifications seemed more complicated than necessary. A classification chart was prepared in 1943 which has since been revised several times to make it more inclusive. The chart shown in Figure 3 was found to be adequate for describing all precipitation which occurred during snow storms in the winter of 1945-46. It was prepared for a group of cooperative observers who assisted the writer in conducting a study of the distribution of crystal forms which occur during widespread snow storms in the northeastern part of the United States.

In order to describe the crystal forms observed, the code number related to the crystal grouping preceded by the letter P is listed. If the crystal structure is coated with cloud particles so that it has a frosted appearance, the letter R following the code number denotes this condition. Thus, the notation P 1R, 6, 8 denotes that at the observation time the snow particles consisted of stellar crystals coated with rime, ice needles, and powder snow. More detailed information on quantity distribution of each form can also be noted by adding a subscript, which indicates the relative amounts in tenths. The forms illustrated on the chart suggest some of the variations which are included under a particular code number.

Table 1 is given to indicate the general features and relative sizes of the precipitation listed in Figure 3.

Table 1--Types of frozen precipitation

1. Stellar crystals	Six rayed, starlike forms occurring as single crystals or in clumps; crystals vary in a wide range of form and size, often comprising cottony flakes sometimes two inches in diameter; size 1/32 inch to 1/2 inch; clumps common
2. Graupel	Snow crystals which are covered with frozen cloud particles forming a rime deposit. This results in pellets of soft snow, which range from hexagonal to rounded kneaded forms; size 1/16 inch to 1/4 inch; rarely clumped
3. Hexagonal plates	Thin, hexagonal, solid or semisolid plates often containing internal structure due to air inclusions. The smallest form of this crystal and the stellar form is known as "diamond dust;" size 1/1000 inch to 3/16 inch; rarely clumped
4. Hexagonal columns	Generally flat-ended, sometimes with one end pointed, hexagonal prisms mostly of transparent ice, many with air inclusions; often a group of columns grow from a common source radiating in several directions. The former type produces 22°- and 46°halos around the Sun; size 1/64 inch to 1/8 inch; sometimes clumped
5. Capped hexagonal columns	Similar to hexagonal columns with the exception that both ends terminate as expanded hexagonal plates; a hexagonal plate sometimes is positioned midway between the two plates. Many queer forms occur; size 1/64 inch to 3/16 inch; sometimes clumped
6. Ice needles	Long slender shafts with hexagonal cross section often terminating with sharp irregular points on periphery; needles occasionally grow in masses in random directions; size 1/64 inch to 3/8 inch; often clumped
7. Asymmetrical crystals	Angular crystals without a symmetrical outline occurring as simple or compound crystals; sometimes crystalline rays originate from a common center but grow in many directions; size 1/64 inch to 1/8 inch; often clumped
8. Powder snow	Dry bits of snow without angular form, often of irregular shape; size 1/64 inch to 1/8 inch; rarely clumped
9. Sleet	Pellets of translucent to transparent ice often bearing bumps or other protuberances; they are frozen rain drops but are not always round; size 1/32 inch to 1/4 inch; very rarely clumped

Preparation of snow-crystal replicas--A method was discovered by the writer [SCHAEFER, 1941, 1942 a] early in 1941 for making exact replicas of snow crystals. A typical replica is shown in Figure 4. This technique consists of coating the crystal with a cold, dilute solution of a synthetic resin. When the solvent evaporates, the unmelted crystal is enclosed by a thin layer of resin. The coating is sufficiently permeable to water or water vapor so that water molecules from the crystal readily pass through the coating, leaving behind a hollow shell whose inside surface is an exact replica of the original surface of the snow crystal. This replica can be studied and photographed under the microscope and shows the external three-dimensional structure of the original crystal. Many modifications of this technique have since been developed by the writer for studying surfaces in both the light and the electron microscope [SCHAEFER, 1942 b, 1943 a, 1943 b].

A very satisfactory solution for making replicas can be prepared by dissolving 15 g of polyvinyl formal resin (Formvar 15-95) in 1000 cc of ethylene dichloride. This solution must be cooled below 32°F before it can be used for ice-crystal replicas.

In practice one of the easiest methods for obtaining replicas is to coat one surface of a glass plate or piece of black signboard with the solution. The coated surface is allowed to drain for a few seconds and then held out in the falling snow for a period of from ten to 60 seconds, depending on the intensity of the storm. In an ordinary storm about 10,000 crystals fall on a square meter each second. As the crystals fall into the solution they are immediately covered by it. After exposure the sample is put in a sheltered place below freezing and the solvent permitted to evaporate. This generally takes from three to five minutes. Best results will follow if the sample is kept below freezing until the crystals sublime. Many modifications of this general technique are possible. Replicas of large deposits of rime or even of fallen snow on the ground can be prepared by using a more concentrated solution--three to five per cent--and making provisions for removing all of the solvent before the sample is handled.

Excellent replicas of snow crystals were made in the aircraft used for studying precipitation static and icing. In order to prevent the breakage of the crystals as they reached the sampling slide, the slide was held several meters from the inlet port so that the velocity was greatly reduced by the time they entered the solution. Another procedure that was used by the writer to obtain good replicas at an altitude of 12,000 feet and an air speed of 200 mph was to employ an air decelerator fastened at the end of a long tube projecting from the nose of a B-24. The decelerator served to "spill" the air, the snow crystals continuing into the quiet air of the tube where they fell into the solution coating, the slide being placed at the closed end of the tube.

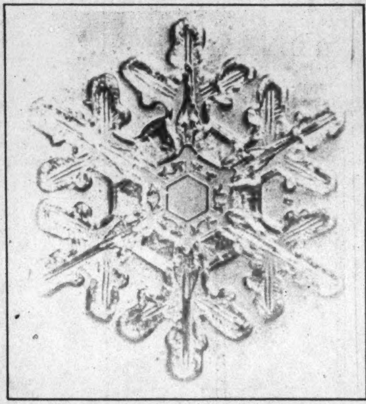


Fig. 4--Typical snow-crystal replica

During the War plastic impressions of snow crystals were also obtained during airplane flights by German scientists [WEICKMANN, 1945]. Unfortunately, they did not use a solution of sufficient dilution so that their replicas did not possess the three-dimensional structure needed to provide a good record of the crystal structure.

In preparing satisfactory replicas either on the ground or in flight, it is very important that everything used in the process is kept below freezing until all trace of solvent has been removed. If the air in the plane is warm, a ventilated cold chamber will achieve this condition. On the ground it is possible to prepare a cold chamber with brine and snow or ice.

Types of atmospheric electricity accompanying snow storms--In the winter period between December, 1943, and April, 1944, a total of 45 snow storms occurred in the Mohawk Valley. Snow accompanying these storms deposited amounts ranging from a trace to as much as 10-1/2 inches in a 12-hour period. Of these storms 22 deposited more than a quarter of an inch, although only eight of them produced more than an inch of snow. Despite the short duration of many of these storms, it was found that in most instances measurements could be obtained or equipment tested so that when extensive storms did occur, all equipment was in working condition.

To obtain information on the atmospheric electricity accompanying snow storms, several types of collectors were used at the snow laboratory at Schenectady. These included a needle point, C_p, a cylinder, C_c, and a blunt ellipsoid, C_b. The form of these collectors and the method used to insulate them from grounding during storms are shown in Figure 5.

The C_b collector was used in field-strength measurements and for this purpose was mounted above a grounded aluminum disc. This collector was connected to a lever system so that it was possible to change suddenly the distance separating the collector from the aluminum disc. When connected to the amplifier-recorder system, the sudden change in relative position between this collector and the metal disc produced an electrical impulse related to the air-to-Earth field at the time of the movement.

To measure the atmospheric electricity picked up by the collectors, amplifier-recording systems were installed at each of the three observation stations.

The amplifiers used were of the D. C. type, each using an FP 54 tube which with 5.3×10^{-10} (amps) gave a full-scale deflection on the record charts of the General Electric photoelectric recorders used with them. A chart speed of six inches per minute was used with the recorders to provide detailed information during short runs, while a speed of six inches per hour was used for observing the atmospheric electrical pattern developed during a storm period.

To eliminate electrical pickup due to radio waves and other sources not associated with atmospheric electricity, a 2.5-millihenry choke was connected in series with the input lead of the amplifier. A switching system made it possible at any time to record in succession within a few seconds the characteristics of the several collectors. At the Research Laboratory two identical amplifier-recording systems were used during the late winter of 1944 to determine the exact relationships between the point and cylinder collectors.

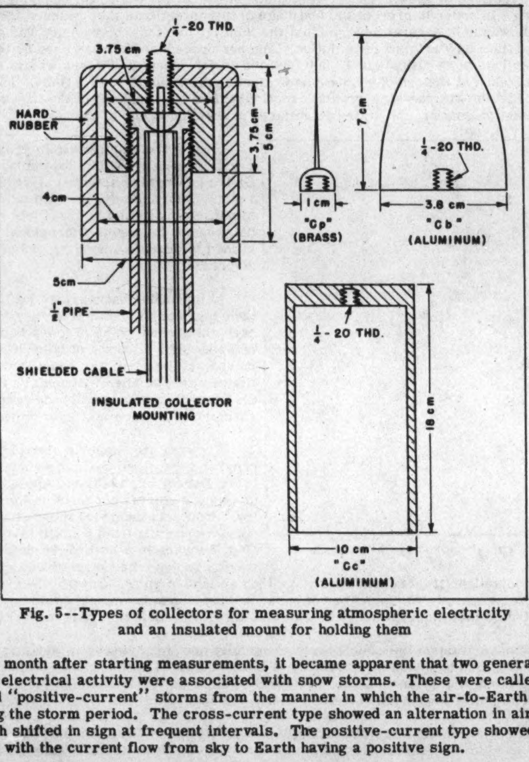
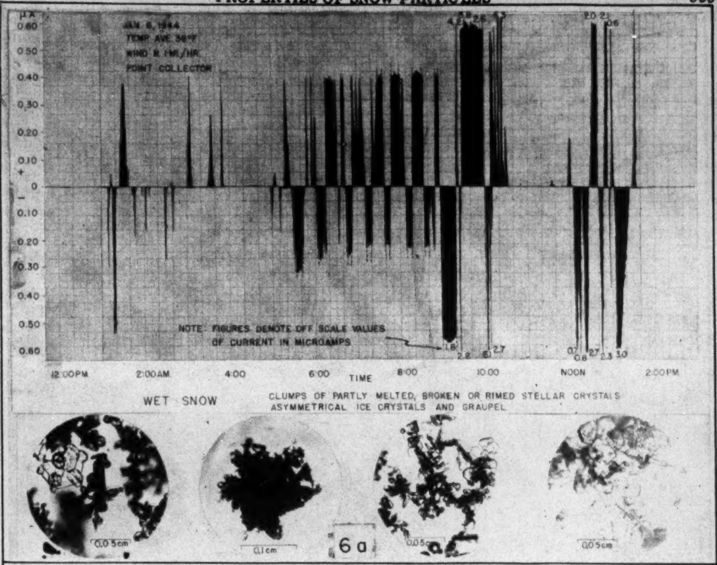


Fig. 5--Types of collectors for measuring atmospheric electricity and an insulated mount for holding them

Within a month after starting measurements, it became apparent that two general patterns of atmospheric electrical activity were associated with snow storms. These were called "cross-current" and "positive-current" storms from the manner in which the air-to-Earth currents flowed during the storm period. The cross-current type showed an alternation in air-to-Earth current which shifted in sign at frequent intervals. The positive-current type showed considerably lower values with the current flow from sky to Earth having a positive sign.

These two types of atmospheric electrical activity were the only kinds observed during snow storms at Schenectady and Mt. Washington. Typical results are shown in Figure 6, which also depicts the crystal forms which fell during the storm period. A summary of the main features found to be associated with these activities is given in Table 2.

The atmospheric electricity measured during the storms considered in Figure 6 is sometimes related to snowfall intensity, but this is not an invariable condition.



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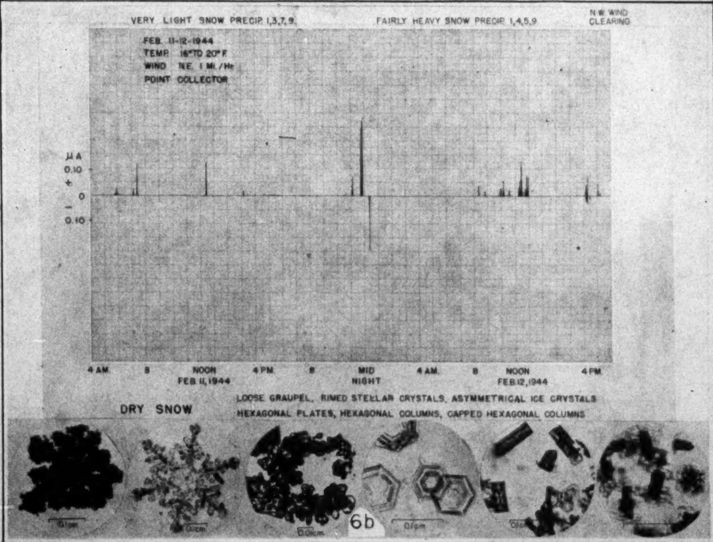
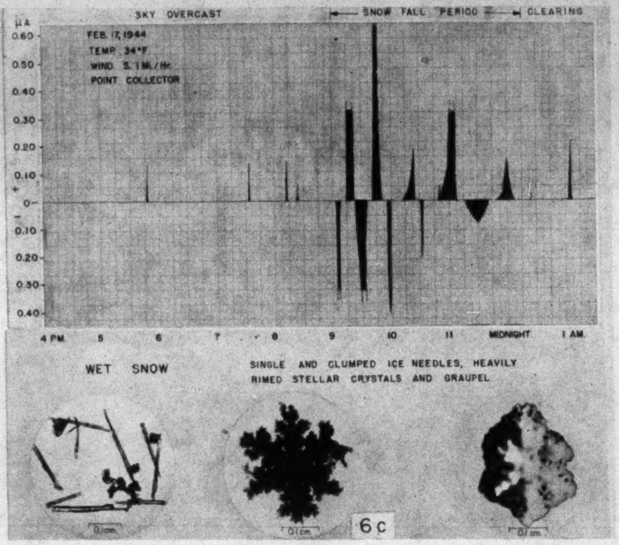


6b

Fig. 6a and b--Typical results of snow-storm observations at Schenectady and Mt. Washington, with crystal forms which fell during the storm period



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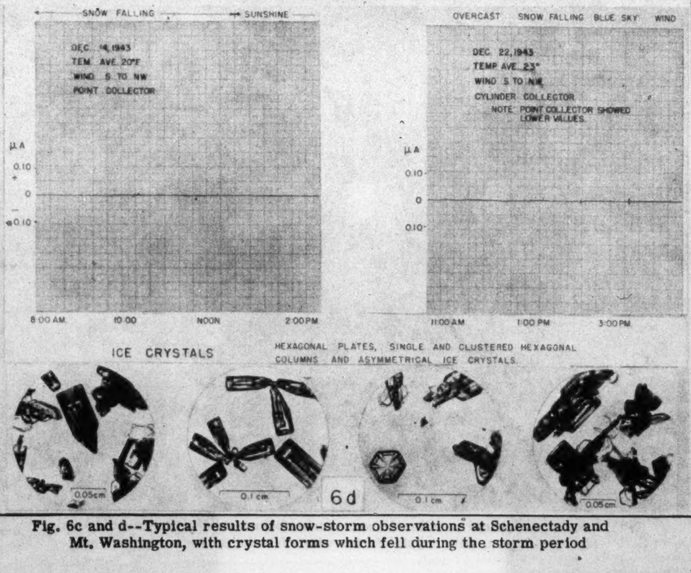
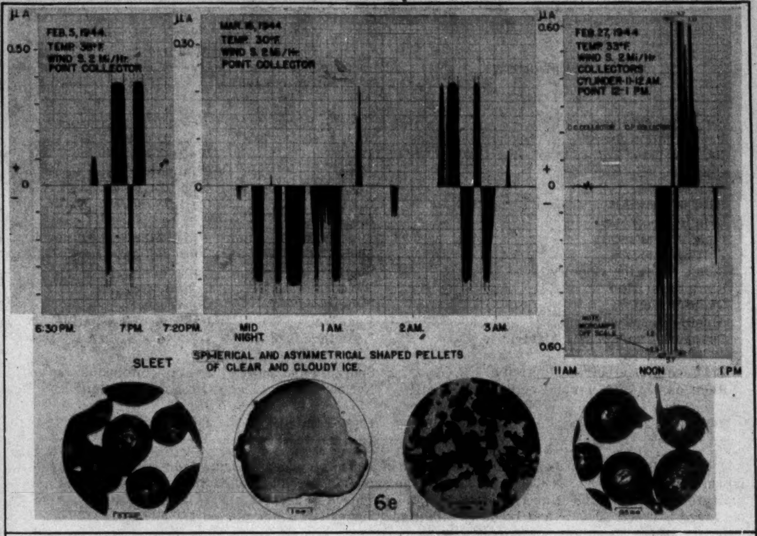


6d

Fig. 6c and d--Typical results of snow-storm observations at Schenectady and Mt. Washington, with crystal forms which fell during the storm period



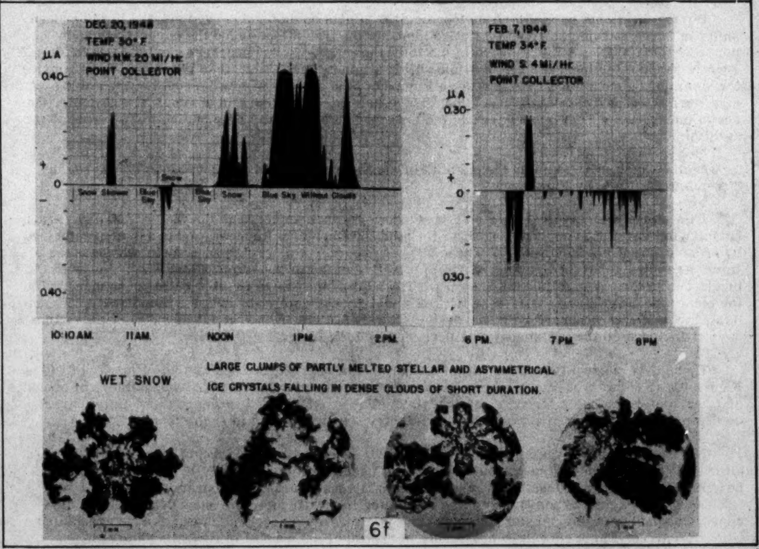


Fig. 6e and f--Typical results of snow-storm observations at Schenectady and Mt. Washington, with crystal forms which fell during the storm period

Table 2--Comparison of general properties of positive and cross-current storms

General properties	Type of storm	
	Positive-current	Cross-current
Air temperature	0 to 25°F	25 to 35°F
Precipitation forms	3, 4, 5, 7, 8	1, 2, 6, 8, 9
General nature of snowfall	Dry	Wettish
Clumping tendency	Rare	Common
Frozen water content	0.05 to 0.2 g/m^3	0.05 to 1 g/m^3
Rate of snowfall	0.1 to 1 cm/hr	0.1 to 3 cm/hr
Density on ground	0.05 to 0.15	0.05 to 0.75
Weight of crystals	4 to 100 micrograms	4 to 1000 micrograms
Falling velocity	50 cm sec^{-1}	20 to 250 cm sec^{-1}
Range of falling velocity	Small	Large
Rime deposition	Rare	Common
Cloud structure	Nonconvective	Convective
Air-to-ground current	Positive	Positive and negative
Observed atmospheric electricity, C_p collector	Less than 0.25 μA	- 7.3 to + 9.7 μA
Frequency of electrical activity	Sporadic and short	Nearly continuous
Relationship of electrical activity to specific clouds	Not obvious	Often quite definite
Rain forms	Light rainfall	Thunderstorms

Figure 6a represents an excellent example of a cross-current storm. During the early-morning period between 01^{h}00^m and 05^{h}00^m the snowfall intensity waxed and waned somewhat as indicated by the electrical activity shown on the graph. A decrease in snowfall intensity was also observed between 10^{h}00^m and 12^{h}00^m, with a very heavy fall in the period 12^{h}00^m to 13^{h}30^m.

During the storm no manifest meteorological effects could be observed related to the sudden shifts in current from positive to negative sign. In the transition period the current would be of the order of 0.00001 μA for a period of 0.5 to two minutes. Following these "quiet periods" the current would often increase 100,000-fold within a minute or so. At other times, as, for example, the storm of February 17, 1944, shown in Figure 6c, the periods of low current between shifts of sign were often of five minutes' duration. The other extreme occurs in some sleet storms such as shown on February 27, Figure 6e, when the low-current period was only of five to 15 seconds' duration.

A clue which might explain these shifts of sign is presented by the conditions observed on December 20, 1944, by Figure 6f.

This storm was a typical series of snow showers, such as occur in the Mohawk Valley region, having wind intensities approaching that of a mild thunderstorm (thunderstorms are characterized by cross-current manifestations). These showers represent discrete air parcels whose outer limits are often apparent when the storm is still five to ten miles away. Cloudless skies with bright Sun precede and follow the showers. The edge of the storm is often quite pronounced, with the transition from clear sky to very limited visibility extremely abrupt. As illustrated in Figure 6, a change of sign occurred with successive showers. Another shower (at 08^{h}00^m) of this same day not included on the graph showed a current of - 1.25 μA.

These data suggest that a well-developed cross-current storm such as that of January 6, 1944, Figure 6a, is comprised of a number of convective air parcels closely adjacent to others of opposite sign, each of which has a strong electrical field. The proximity and extent of these finite parcels determines the intensity of the atmospheric electricity encountered in such storm areas.

Of added interest in the storm of December 20, 1944, is the atmospheric electricity observed after 12^{h}30^m which occurred without any trace of precipitation in the air. It is believed that this field was originally produced by snow particles which subsequently disappeared because of sublimation. The excess of positive charges remaining in the air after the snow particles had disappeared would probably persist for some time in a discrete parcel which would have associated with it an air-to-Earth current considerably in excess of the normal fair-weather current.

Since these records were obtained, many observations of a similar nature have been noted. The evidence suggests that the effect is caused by the evaporation of charged snow crystals falling into dry air. The air parcel which contained the crystals persists in a charged condition until the charges are either neutralized or leak off to the ground. This charged condition probably persists for a longer time than if the crystals had not evaporated, since diffusion, which controls the discharge, proceeds at a considerably slower rate than if the charges were carried to the Earth by falling crystals.

These "ghost storms" are fairly common and occur most often associated with the advance of a frontal system. They will be referred to again in a subsequent section.

Actual records of atmospheric electricity as obtained at Schenectady are shown in Figure 7. Chart 1 of Figure 7 shows synchronous traces obtained with a point, C_p, and a cylinder, C_c, collector each having its own amplifier-recorder system previously described. These records were made during low electrical activity. Section b of this chart shows clearly the relationship which exists at periods having no precipitation. Under such conditions, it is apparent that the cylinder indicates changes in field strength when there is no precipitation in the air to deliver charges to it. Thus, when the field increases to a maximum the cylinder trace shows a peak either on the positive or negative side of zero. At this instant the point collector (dotted line) shows a current flow. As the field strength reaches a maximum rate of change the cylinder trace (solid line) passes through zero and reaches a limiting value of opposite sign as the current from the point collector drops to zero. Since it apparently takes considerable field strength to bring the point collector to corona and thus show a measurable current, the cylinder is more sensitive of the two collectors. Once the point starts carrying current it shows higher values than the cylinder, since the field is more intense at a point than at a blunt object like the cylinder.

Chart 2 shows typical results obtained with the three collectors observed in succession. These traces were obtained during the positive-current storm of February 11, 12, 1944. The first series was obtained as a definite lull occurred in the storm. At this time there was a negative field of 250 V/cm and both point and cylinder showed low negative currents. Thirty-two minutes later the field had shifted to a positive sign of 120 V/cm with point and cylinder both showing positive currents. Not long afterward the type of snow crystal changed from stellar crystals and graupel to hexagonal plates and columns. The next morning during a period of considerable current flow at 11^h22^m a measurement was made which showed a field of + 1100 V/cm. At this time a current of + 0.064 μA was flowing to the point collector and + 0.0015 μA was obtained with the cylinder.

On March 31, 1944, a rather intense snow squall of the cross-current type occurred late in the afternoon. During this shower synchronous recordings were made of the current obtained by the point and cylinder collectors. A three-minute period of these two records is shown in Chart 3. In this case the cylinder collector, besides showing characteristic fluctuations in field potential, has superimposed the average net charge delivered by the falling snow flakes. The net effect of the charged snow flakes tends to keep the cylinder current biased in the direction of the sign carried by the point collector. The current collected by the cylinder was in general about one-fifth of that obtained with the point collector.

Chart 4 shows the type of records obtained during a positive-current storm. It is of special interest to observe the very rapid fluctuations which occurred at the end of the storm as the wind shifted and rather violent gusts of wind and blowing snow swept around the laboratory.

Charts 5 and 6 show rather interesting unusual electrical activity which occurred without precipitation. In both instances the shift in sign of the current from negative to positive was followed by precipitation, within six to 12 hours. A further treatment of these phenomena will be carried on in a discussion of Figure 15.

While these measurements of atmospheric electricity were being made at the snow laboratory in Schenectady, attempts were made to carry out similar studies at the Mt. Washington Observatory. Serious difficulty was experienced in keeping the collectors free of ice deposits. During nearly all snow storms on the mountain, clouds of supercooled water droplets accompanied the snow. These supercooled droplets occur in clouds with temperatures of 0°C to -35°C on Mt. Washington. As soon as they contact a solid surface, the particles freeze, the resulting ice formation growing into the wind in various types of structures ranging from a smooth glaze to delicate featherlike forms.

Although ice is normally a good insulator, the formation of rime ice on an insulator produces serious leakage. Measurements made with a 1.5-volt battery placed in series with a collector

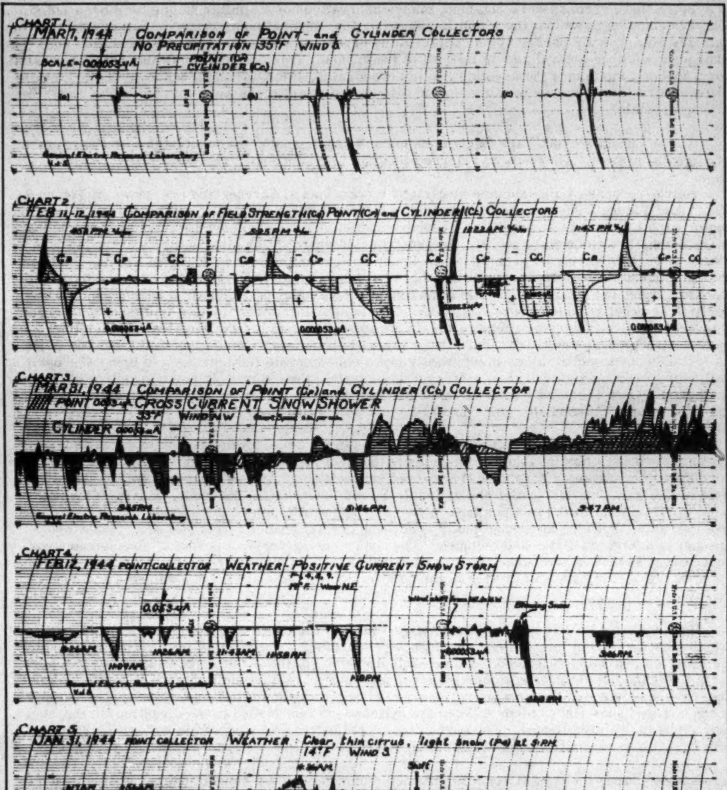


Fig. 7--Sample records of atmospheric electricity in the winter of 1944 at Schenectady, New York insulated with 3.7-cm hard rubber bushing showed the following leakage conditions. With rime ice forming at a rate of 2.5 cm/hr, 15 seconds after the collector-insulator system was exposed to the storm, the insulation resistance had dropped from infinity to 500 megohms. In one minute this resistance was 200 and after an hour, it was 15 megohms. This leakage is probably caused by a very thin layer of liquid water which persists for an instant before freezing.

Although it was nearly impossible to make long runs to study atmospheric electricity at the Observatory with the collector system available, enough data were obtained to show that the results obtained at the snow laboratory at Schenectady were the same as those which occurred on the mountain.

The work on Mt. Washington was carried out in cooperation with E. J. Lawton and H. E. Tanis of the General Electric Research Laboratory and with V. F. Clark, R. E. Falconer, and K. E. Gould of the United States Weather Bureau and Mt. Washington Observatory staff. Much credit is due these men for their enthusiastic participation in this difficult research project.

Electric charge carried from the sky by falling snow crystals--To determine the relative importance of the phenomena thought to be responsible for the occurrence of precipitation static on aircraft and other electrical effects sometimes observed at ground stations during snow storms, it was necessary to obtain quantitative measurements of the factors involved. Two of these studies involved the determination of the quantity and sign of the charge carried by single snow crystals and the total average charging current produced as large numbers of crystals fall from the sky. Other investigators [NAKAYA and TERADA, 1934; SCHWEND, 1920; SIMPSON, 1910] have made somewhat similar measurements. Nakaya and Terada used a snow chimney, but their results did not permit a quantitative determination of the quantity of charge carried by the individual crystals.

The charged condition of a crystal and its sign (whether positive, negative, or neutral) was determined by having the crystal fall down a "snow chimney" and thence into a strong electric field. This snow chimney had a cross section of 30 × 37.5 cm and was 3.6 meters in height. Immediately below the base of the chimney, a cleanout section was provided for removing accumulated snow. In the center of this space a shutter was located having an aperture 2.5 cm square. This shutter was arranged so that it could be opened from within the laboratory to permit free-falling snow crystals to enter the snow chamber. To keep air currents from affecting the free fall of the snow crystals, a removable cylindrical tube 13 cm high and five cm in diameter, having an aperture 2.5 cm in diameter at the top was placed above the sliding shutter. The snow chimney, shutter, and aperture were grounded at all times.

Below the shutter was the snow chamber where observations were made on the velocity of fall, electrical charge, and sign of the charge of the snow crystals. The chamber was fitted with an air-tight door having a glass window. The interior of the chamber was coated with a dull black paint to improve contrast when making photographs.

In the chamber two vertical brass plates 28 cm × 15 cm × 0.2 cm were mounted on insulators. These plates were placed parallel to each other with a distance of 7.8 cm between them. A vertical slot in each plate 1.5 cm in width permitted light from two H4 high-pressure mercury lamps to illuminate the falling snow crystals. As these lamps were actuated by 60-cycle alternating current, they produce light of an intermittent nature, with flashes occurring every 1/120 second. The crystals falling into the chamber appear as dotted white lines, the time interval between the successive dots being 8.3 milliseconds. A schematic diagram of the installation is shown in Figure 8.

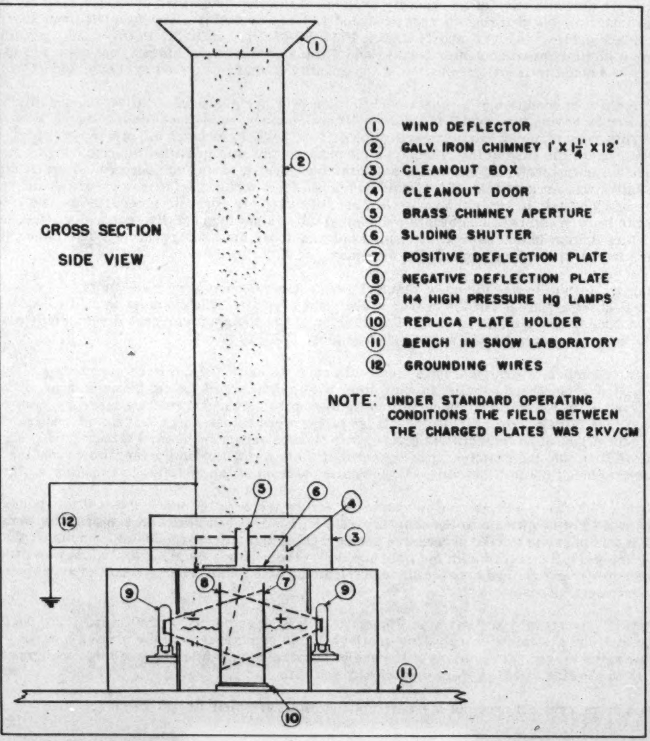
With a 16 kv high-voltage source connected across the parallel brass plates it was possible to apply a field of two kv/cm to the snow crystals falling between them. A camera was arranged so that it was possible to take successive photographs within a few seconds of each other; the first without any field, the second with the field applied to the region. By using a film pack an exact relationship was maintained between the electrical and other atmospheric conditions existing during the experimental exposure period.

Typical photographs are shown in Figure 9. It will be noted that without a field the particles fell vertically in a straight or spiralling motion. In the electric field some particles curved to the positively charged plate, others to the one of negative sign, while many of them were unaffected by the field showing that they were electrically neutral.

Data from a typical group of measured photographs are tabulated in Table 3.

Table 3--Electric charge

Photo 8B, 09^h05^m, February 12, 1944					Photo 1B, 16^h25^m, February 11, 1944				
Precipitation	v, cm sec^{-1}	m, μG	tan θ	esu × 10^{-6}	Precipitation	v, cm sec^{-1}	m, μG	tan θ	esu × 10^{-6}
Hexagonal plates	51.0	8.0	- 0.06	+ 70	Wind	63.0	13.5	0	0
	59.0	11.5	- 0.095	+ 160	Crystals	22.5	1.4	+ 0.10	- 20
Hexagonal columns	20.0	1.0	- 0.45	+ 66	Stellar crystals	45.5	6.4	+ 0.10	- 100
	58.0	11.0	- 0.023	+ 37		17.5	0.8	+ 0.23	- 30
Capped hexagonal columns	48.0	7.0	- 0.10	+ 102	Powder snow				
	49.0	7.4	0	0					
	57.0	11.0	0	0					
Powder snow	42.0	5.2	+ 0.21	- 160					
	40.0	4.8	+ 0.20	- 140					
	63.0	13.5	+ 0.18	- 360					
	56.5	10.6	+ 0.025	- 39					
	94.0	40.0	+ 0.01	- 60					



CROSS SECTION
SIDE VIEW
① WIND DEFLECTOR
② GALV. IRON CHIMNEY 1' X 1¼' X 12'
③ CLEANOUT BOX
④ CLEANOUT DOOR
⑤ BRASS CHIMNEY APERTURE
⑥ SLIDING SHUTTER
⑦ POSITIVE DEFLECTION PLATE
⑧ NEGATIVE DEFLECTION PLATE
⑨ H4 HIGH PRESSURE Hg LAMPS
⑩ REPLICA PLATE HOLDER
⑪ BENCH IN SNOW LABORATORY
⑫ GROUNDING WIRES
NOTE: UNDER STANDARD OPERATING CONDITIONS THE FIELD BETWEEN THE CHARGED PLATES WAS 2KV/CM
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑨
⑩
⑪
⑫
-
+

Fig. 8--Snow chimney, deflecting plates, and velocity-of-fall device on single particles of snow

Photo 7B, 08^h20^m, February 12, 1944

Precipitation	v, cm sec^{-1}	m, μG	tan θ	esu × 10^{-6}
Hexagonal plates	69.0	16.5	+ 0.058	- 140
	65.0	14.5	+ 0.020	- 43
Capped hexagonal columns	36.0	3.8	+ 0.05	- 28
	35.0	3.6	+ 0.02	- 10
	54.0	9.4	+ 0.05	- 70
	50.0	7.6	+ 0.02	- 22
	74.0	20.0	+ 0.012	- 35
	34.0	3.5	0	0
	68.0	16.0	- 0.12	+ 280
	50.0	7.6	- 0.11	+ 120
	32.0	3.0	- 0.02	+ 14

Photo 10B, 11^h05^m, February 11, 1944

Precipitation	v, cm sec^{-1}	m, μG	tan θ	esu × 10^{-6}
Hexagonal columns	40.0	4.8	- 0.061	+ 43
	117.0	70.0	- 0.012	+ 124
	82.0	27.0	+ 0.075	- 300
	32.0	3.1	+ 0.143	- 66
	38.0	4.3	+ 0.072	- 46
	57.0	10.6	+ 0.081	- 126
	40.0	4.8	+ 0.73	- 530

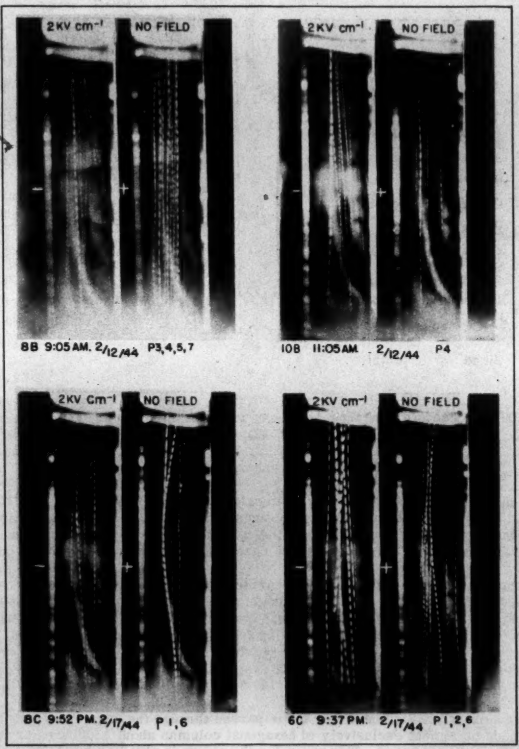

2KV cm⁻¹
NO FIELD
-
+
8B 9:05AM. 2/12/44 P3,4,5,7
2KV cm⁻¹
NO FIELD
-
+
10B 11:05AM. 2/12/44 P4
2KV cm⁻¹
NO FIELD
-
+
8C 9:52 PM. 2/17/44 P1,6
2KV cm⁻¹
NO FIELD
-
+
6C 9:37 PM. 2/17/44 P1,2,6

Fig. 9--Typical photographs of snow crystals falling into snow chamber

These data, which were obtained by the writer, were analyzed by Langmuir as part of his theoretical study of precipitation static. The charge on the particle was determined by the relation of the mass of the particle to the deflection angle in the field. The mass was determined from the velocity of fall and from examination of the crystals. The charge was calculated from Equation (1).

$$\text{esu} = 0.148(M \times 10^{6})\tan\theta \; 10^{-3} \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Of the many particles measured, the crystal having the maximum charge had a value of -5.3×10^{-4} esu. The average net charge, however, of those deflected in the field shows a value of about -1.0×10^{-4} esu.

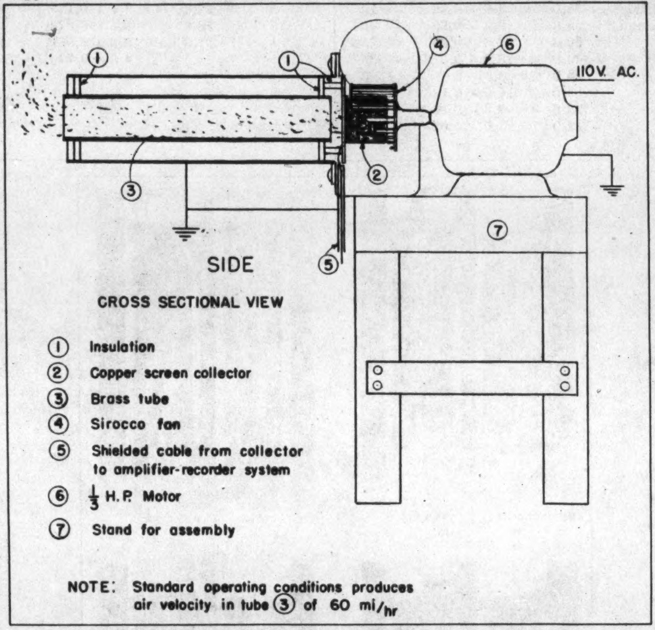

①
①
④
⑥
110V. AC.
②
③
⑦
⑤
SIDE
CROSS SECTIONAL VIEW
① Insulation
② Copper screen collector
③ Brass tube
④ Sirocco fan
⑤ Shielded cable from collector to amplifier-recorder system
⑥ 1/3 H.P. Motor
⑦ Stand for assembly
NOTE: Standard operating conditions produces air velocity in tube ③ of 60 mi/hr

Fig. 10--Snow-charge indicator

Thus, the charged crystals on the average carried approximately 200,000 electron charges as they approached the ground. Many crystals, however, failed to show any charge. Since the charged crystals had either positive or negative signs, the combined effect of a large number of crystals gave a lower charging current than would be the case if they were all charged with only one sign.

To obtain an average value of the charges carried by the falling snow crystals another apparatus was used, patterned after the Faraday cage. A wire mesh "pail" was mounted on insulators at one end of a 46-cm-long brass tube 10.2 cm in diameter. This collector was in turn mounted on a suction blower so that air containing free-falling snow crystals passed through it and the crystals delivered their charge as they reached the insulated cage. A shielded cable passed from the cage to the amplifier recording system. All parts of the apparatus, except the cage, were grounded. A schematic diagram of this apparatus is shown in Figure 10.

In use, approximately 0.2 cubic meter of air passed through the cage every second. In a typical storm made up almost exclusively of hexagonal columns about 2300 snow crystals were sucked into the cage every second. This value for the storm is obtained by dividing the frozen water content of the air, which had a value of 0.171 g/m^3, by the average weight of a single hexagonal-column ice crystal Ca 15 micrograms.

To make a measurement of the net charging effect, the snow-charge indicator was run for several minutes in synchronism with the amplifier-recording system. The resulting record showed a time-current relationship. By measuring the area of this record with a planimeter and knowing the approximate number of crystals producing the effect, a value was obtained showing the average net charge per crystal. A typical measurement during a fall of hexagonal columns such as occurs in cirrus clouds showed a net charging current of + 3.9×10^{-3} esu/sec.

Other studies [MacCLELLAND and NOLAN, 1912] of the average charge carried to the ground by snow during a storm show conflicting results. SIMPSON [1910] observed more positive than negative charges on snow. MacCLELLAND and NOLAN [1912] checked this result, finding that larger snowflakes tended to have positive charges while the smaller ones showed a negative sign. Kohler, however, found opposite results, finding more negative than positive charges on snow particles. NAKAYA and TERADA [1934] checked Kohler's results in general, although they found that at times during a storm there were as many as 2.4 times more positive than negative crystals. Their average result, however, showed that there were about 1.4 times more crystals carrying a negative charge.

The number of crystals analyzed in studies of this kind is but a minute portion of the total snowfall. For example, with a value of 0.175 g/m^3 representing the weight of snow crystals in a cubic meter of air during an average storm, a falling velocity for the crystals of 50 cm sec^{-1}, and an average weight per crystal of 15 micrograms, approximately 5750 crystals reach a square meter of ground every second. Thus, it is not surprising that conflicting data have been obtained in the process of sampling storms.

It will be shown in a subsequent chapter that the electric charge carried by snow particles is of minor importance in the production of static electricity during a snow storm.

Terminal velocity of falling snow crystals--It is necessary to establish the terminal velocity at which various types of snow crystals fall from the sky, in order to calculate the number of particles encountered by an airplane in flight. To do this photographs were made such as are shown in Figure 9. The crystals falling into the snow chamber were illuminated by light from H4 high-pressure mercury lamps. When these lamps are actuated with 60-cycle alternating current, a stroboscopic effect is produced as the gaseous discharge with A. C. occurs every 1/120 second (8.3 milliseconds). Thus, a falling crystal appears to the observer as a line of white streaks. Knowing the height of the visible area, only a simple measurement of the number of consecutive streaks is needed to establish the falling velocity of the snow crystals. By preparing replicas of the snow crystals as the exposure was made, a permanent record was obtained showing the type of crystals which produced the photographic record.

Some years ago NAKAYA and TERADA [1935] made observations of velocity of fall by a more involved procedure than the one described. The data obtained by them are included in Table 4. These combined results show that a value of 50 cm sec^{-1} for the average falling velocity of snow particles provides a convenient round number that is characteristic of a large percentage of snow particles in most snowstorms.

Production of frictional electricity by the fragmentation of snow crystals--The measurement of electric charges carried by falling snow crystals just described demonstrates that although snow particles often carry a charge as they fall from the sky, the quantity of the charge is inadequate to account for the intense electrical effects experienced by aircraft flying through snow storms.

In order to determine whether frictional effects associated with the fragmentation of snow particles were primarily responsible for this phenomenon, an apparatus was constructed which is shown in the schematic drawing of Figure 11.

This consisted essentially of a high-speed motor producing a suction capable of accelerating snow particles to a speed of 60 mph. The particles were accelerated by having them pass into a grounded brass tube 1.9 cm in diameter and 31 cm long. The front end of the tube was constricted to 1.6 cm in diameter to keep the incoming snow particles from rubbing on the side of the intake tube as they passed into the fragmentation chamber. After being speeded up, the particles hit an insulated 2.5 × 7.5-cm aluminum plate held at an angle of 45 degrees with respect to the axis of the intake tube. Upon reaching this plate, the particles or fragments bounce to another insulated metal plate parallel to the first, bounce again, continue through the blades of the suction motor, and are then discharged as a fine ice powder into the air.

Shielded cables joined the aluminum plates to the amplifier-recorder system so that the charging effect caused by friction and breakage can be measured in a quantitative manner.

To determine what happens to snow crystals which hit a solid surface at high velocity, replicas were made in the snow-impact apparatus during snow storms. Glass plates coated with the replica solution previously described were substituted for the metal plates and snow particles of a specific size and crystal structure were introduced at the entrance of the intake tube. Under the operating conditions used, the crystals struck the first plate with a velocity of about 60 mph.

Table 4--Velocity of fall of snow particles

Snow-crystal types	Code number	Number of observations	Fastest	Slowest	Average
			cm sec^{-1}	cm sec^{-1}	cm sec^{-1}
Stellar crystals	1	8	113	17	41
Powder snow					
Hexagonal plates	3	29	95	32	54
Capped hexagonal columns	5				
Hexagonal plates	3	26	102	20	56
Hexagonal columns	4				
Capped hexagonal columns	5				
Powder snow	8				
Hexagonal columns	4	17	117	29	56
(After Nakaya)					
Ice needles	6	5	25	65	50
Stellar crystals	1	13	25	35	31
Powder snow	8	9	40	55	50
Rimed stellar crystals	1	4	90	110	100
Graupel	2	7	260	120	180

Using a one per cent replica solution, the high air speed caused the solvent to evaporate very rapidly, so that excellent replicas were obtained of the broken crystals at the second collector-plate location after the crystals hit the first plate. A replica was also made of the fragments after passing through the suction fan. Both stellar crystals and hexagonal plates and columns were used. Photomicrographs of the original forms and fragmentation replicas are shown in Figure 12.

Planimeter measurements of the areas of the original crystals and the fragments which remained after hitting the metal surface show that stellar crystals having a velocity of 60 mph are broken into about 500 pieces when they hit an aluminum surface inclined at a 45-degree angle. Hexagonal plates and columns are broken into about 30 fragments under similar conditions. These latter crystals, however, are one-tenth to one-fifth as large as the stellar forms and are much less fragile. After passing through the high-speed suction fan, the fragments are further reduced in size by a factor of about five.

These results indicate the type of fragmentation that occurs when snow particles hit the leading edge of an airplane wing or come into contact with its propellers. The range of even the smallest snow particles encountered in ordinary storms is sufficiently high so that they reach such surfaces at velocities considerably greater than used in the snow-impact apparatus. The fragmentation of snow crystals under flying conditions will therefore be even greater than shown.

Besides using clean metal plates for collectors in the snow-impact apparatus a study was made to determine whether plastic coatings would alter the charging effect produced by snow. Among the coatings used were ethyl cellulose and nitrocellulose applied by dipping from five-per cent solutions. The coatings were 0.01 cm thick. Typical results are shown in Table 5.

These show that with one exception in storms of either cross- or positive-current type the uncoated aluminum always developed a positive charge. The one exception occurred in a storm when the point collector showed a negative sign. Shortly afterward, when the current flow with respect to ground reversed to a positive sign, the plate showed the usual amount of positive charge.

When the metal plate was coated with nitrocellulose lacquer, the charge which developed invariably had a negative sign and the current measured was from two to more than five times as great in terms of electrostatic units per gram of snow.

When the plate was coated with ethyl cellulose, the charge developed was nearly identical with that of the uncoated metal.

These results show that when aluminum wings on aircraft are covered with camouflage made with a nitrocellulose base, it is likely that such a coating will produce a five-fold increase in the charging current when the plane flies into a snow storm. An unpainted plane is to be preferred over a plane having any coating thus far developed. It is possible, however, that a coating might be found that would be electrically neutral toward snow. If such a coating is found, it will be very useful in suppressing precipitation static.

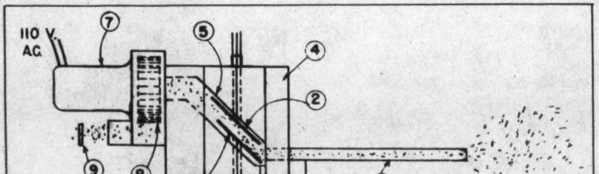

110 V.
AC
⑦
⑤
④
②
⑨
⑧
①
③
⑥
TOP VIEW
① Test plate position #1
② Test plate position #2
③ Brass intake tube
④ Wooden block
⑤ Lead foil lined passageway
⑥ Shielded cable to amplifier-recorder system
⑦ High speed vacuum cleaner motor
⑧ Suction fan
⑨ Test plate position #3
NOTE: Standard operating conditions produces air velocity in tube ③ of 65 mi/hr

Fig. 11--Snow-impact apparatus

It is interesting at this point to compare the average net charge carried by falling snow crystals with the charge developed when they hit a surface at high velocity. A few typical examples of quantitative measurements are given in Table 6. These data show that the charging current developed by high-velocity impact, friction, and fragmentation of crystals produces from 15 to at least 130 times more charging current than is measured when naturally-charged free-falling crystals contact a surface at low velocity. This indicates the probable source of much of the high charge which leads to precipitation static on aircraft flying through snow storms.

Range of snow particles in quiet air--In order to determine the distance that snow particles will travel through quiet air after they have been accelerated by wind or when approached by a fast-moving air foil, an apparatus was assembled as indicated by Figure 13. Particles falling within the influence of the air intake at nozzle 2 in Figure 13 are accelerated in tube 3 for a distance of 32.5 cm with air having a velocity of 83 mph. The end of this tube is flared so that the

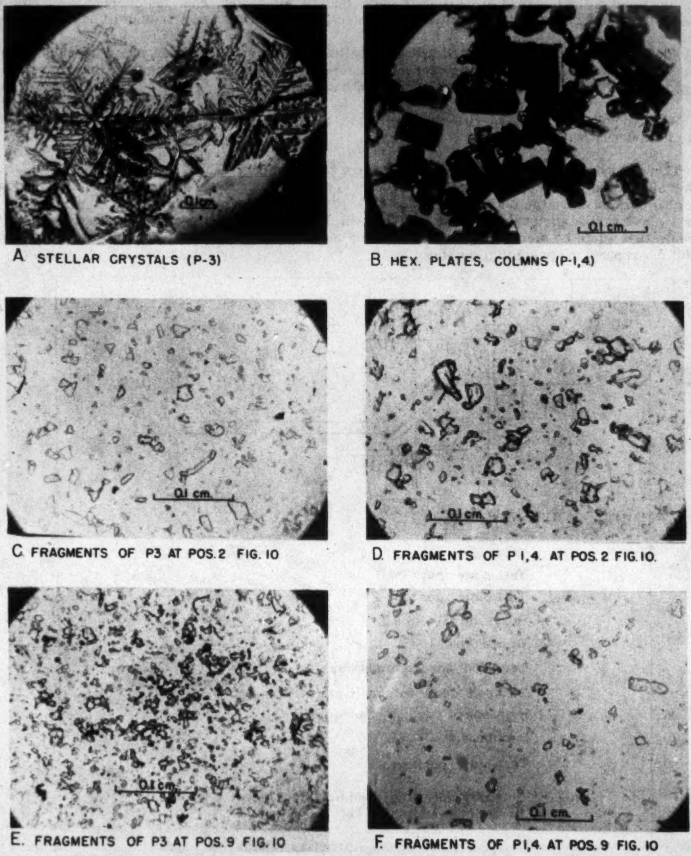

0.1 cm.
A STELLAR CRYSTALS (P-3)
B HEX. PLATES, COLMNS (P-1,4)
C FRAGMENTS OF P3 AT POS. 2 FIG. 10
D FRAGMENTS OF P 1,4 AT POS. 2 FIG. 10.
E. FRAGMENTS OF P3 AT POS. 9 FIG. 10
F FRAGMENTS OF P1,4 AT POS. 9 FIG. 10

Fig. 12--Photomicrographs of original forms and fragmentation replicas, showing effect of impact on snow crystals

high-velocity air spreads and is "spilled" by louver 4. An aperture is located just beyond this point through which the accelerated particles travel. This is the entrance to an otherwise closed box having a sheet of black velvet on its lower surface. Table 7 lists the results obtained using methylmethacrylate spheres with this apparatus.

The range of snow particles accelerated by this arrangement can be determined by several methods. The simplest method, of course, is visual observation and classification of size and shape. In many instances this procedure must be carried out under the microscope since the particles are too small for observation with the unaided eye. Since small crystals often have a short life span, a photographic record must be made as rapidly as possible after they have entered the ranging box.

Table 5--Development of electricity in snow-impact apparatus

Type of storm	Date	Time	Temperature	Type of precipitation	g/m^3	Dural 17ST			
						Surface coating			
						Uncoated	0.01 cm ethyl cel. (3570 - 30 - 4)	0.01 cm nitrocel. (3570 - 30 - 5)	0.012 cm 25 nitrocel. 25 ethyl cel. (3570 - 30 - 6)
			°F			esu/g	esu/g	esu/g	esu/g
Cross-current	January 23, 1944	$09^{h}17^{m}$	34.0	1, 5, 8	1.071	+ 1.9	. . .	. . .	. . .
Positive-current	January 31, 1944	$18^{h}01^{m}$	29.5	1	0.242	+ 12.7	+ 27.8	- 24.3	- 9.2 + 17.4
	January 31, 1944	$17^{h}18^{m}$	29.5	4, 7	0.161	+ 51.0	+ 22.3	- 92.5	. . .
Positive-current	February 11, 1944	$16^{h}35^{m}$	19.0	1R[a]	0.094	+ 60.2	+ 84.5	- 139.5	- 24.5
	February 11, 1944	$22^{h}13^{m}$	16.5	3, 4, 7	0.188	+ 48.0	+ 10.5	- 148.5	- 51.3
	February 12, 1944	. . .	18.0	4	0.176	+ 15.2	+ 8.4	- 70.2	- 11.1
Positive-current	February 16, 1944	$14^{h}37^{m}$	30.0	4R[a]	0.141	+ 8.3	- 14.6	- 34.4	- 16.5
Cross-current	February 17, 1944	$21^{h}53^{m}$	34.5	1R[a], 6, 8	0.518	+ 7.3	- 8.5	- 14.0	- 9.8
	February 17, 1944	$22^{h}01^{m}$	34.5	1R[a], 6, 8	0.518	+ 9.7	. . .	. . .	. . .

[a] R indicates crystals are coated with rime.

Table 6--Comparison between average charge carried by snow crystals and electrification produced by friction and fragmentation

Type of storm	Date	Time	Temperature	Liquid H_2O	g/sec	esu/sec × 10^{-2}	esu/g	esu/g of snow impact / esu/g of snow charge
			°F	g/m^3				
Positive	February 11, 1944	16^h33^m	19.0	0.094	0.0191	+ 1.26	+ 0.66	91.0
Positive	February 11, 1944	22^h13^m	16.5	0.188	0.0382	+ 0.96	+ 0.25	120.0
Positive	February 12, 1944	10^h24^m	18.0	0.176	0.0358	+ 0.39	+ 0.11	137.0
Positive	February 16, 1944	14^h37^m	30.0	0.141	0.0286	+ 1.32	+ 0.46	18.2

Table 7--Range of methyl methacrylate spheres, air velocity 83 mph, acceleration distance 32.5 cm, specific gravity 1.18 - 1.19

Diameter of particle	Range of particle
cm	cm
0.0120	26.5
0.0147	52.5
0.0186	81.5
0.0237	103.5
0.0356	132.5

A more convenient and much easier procedure is to make permanent replicas of the crystals as they fall in the ranging box. Strips of glass or black cardboard are coated with the replica solution and placed on the floor of the ranging box. As the snow particles enter the box their trajectory brings them to rest in the solution. Within a few minutes the solvent evaporates leaving plastic replicas which are accurate representations of the size, shape, and thickness of the original particles. These may be studied at leisure and selections made of representative samples which may be measured directly under the microscope and photographed for the record. This method is particularly suited for thickness measurements since only the surfaces of the snow particles are preserved. Using the calibrated fine adjustment on the microscope, the upper and lower surfaces of the replica can be brought into focus and the thickness determined with ease.

Since the number of snow particles falling within the influence of suction of the snow-ranging device is quite limited, it was found that good samples could be obtained by gathering up a loose clump of freshly-fallen dry snow and letting it enter the opening of the acceleration tube. By this procedure, using a fairly large quantity of particles, a good measure of the range distribution in a particular type of storm could be obtained.

Such observations showed that with storms of ice crystals in which the particles were between about 0.05 and 0.01 cm in effective diameter, the distance traveled with air velocity of 83 mph lay between 30 and 80 cm, with the greatest number in the vicinity of about 50 cm. Such types of ice crystals probably constitute forms often encountered by aircraft in both positive- and cross-current types of precipitation static. The actual velocity of a particle of 0.05-cm effective diameter starting at rest and receiving acceleration from air velocity of 83 mph for a distance of 32.5 cm is of the order of 55 mph.

The asymmetry of many snow particles such as powder snow and the considerable difference of length, breadth, and thickness of symmetrical crystals are important factors in fixing their range. Figure 14 shows a group of line drawings of snow particles with data on types whose range was determined by the method described above.

Number of snow particles encountered by aircraft in snow storms--In evaluating the charging currents measured on aircraft or other objects, it is important to know the number of crystals encountered. As shown previously in this paper, the range of snow particles is so great even at a velocity of 50 to 60 mph that all particles in the path of the frontal area of a plane will reach its surface. Thus, it is necessary to determine the frontal or projected area of the object under consideration, the average number of crystals, and their weight in a cubic meter of air.

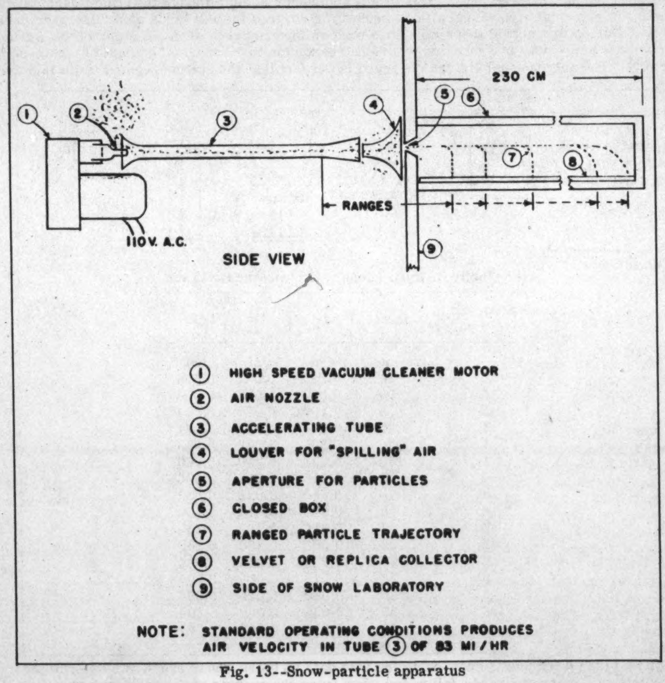
A typical example is as follows. The projected frontal area of a B-29 is approximately 60m^2. The air velocity is 300 mph; frozen water content of air, 0.175 g/m^3; velocity of fall of crystals, 50 cm sec^{-1}; and weight of a single crystal, 15 micrograms. With these values it follows that the plane would pass through 8640 cubic meters per second, each cubic meter of air containing about 11,500 crystals. Thus, a B-29 travelling at a speed of 300 mph encounters approximately ten billion snow crystals each second of flight through a snowstorm.

Atmospheric electricity related to the passage of fronts--In the course of making records of the atmospheric electricity accompanying snow storms, it was decided to make continuous recordings throughout the day and night regardless of weather conditions. The results obtained in the period January 9 to February 16, 1944, are presented in Figure 15.

Of the three collectors previously described it was decided to use the point collector on this continuous run for several reasons. Although the cylinder collector often showed readings during clear weather when the point was insensitive, it was found that these readings were related to the change in potential gradient. While such readings showed some variation, these were in general of small magnitude. Synchronous runs with the two collectors showed that whenever a change of considerable magnitude occurred, the point collector invariably produced a record. Since these larger effects would seem to be the important aspect of atmospheric electricity, it was decided to use the point rather than the cylinder for making continuous runs. An insulation resistance of from one-tenth to 1/100 of that needed with the cylinder could also be used with the point collector. Because of these lower resistance requirements, very few insulation troubles were encountered when the point was used even in "wet" weather.

The relation of atmospheric electricity to meteorological phenomena has been the subject of study by a number of investigators. The results of some of these workers have been referred to in a paper by ROSE [1937].

In the paper cited, Rose concludes, "The study of disturbances in the potential gradient shows that all disturbances can be correlated with local meteorological conditions." His studies showed that the potential gradient generally displays a state of disturbance several hours before and after the passage of a front, but that the time relation to the passage of the front varied so much that no definite rule could be made about it.


①
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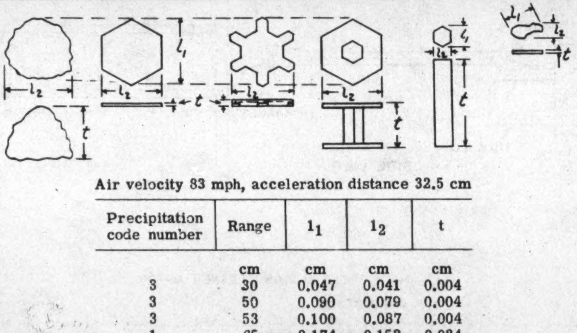
230 CM
RANGES
110V. A.C.
SIDE VIEW
① HIGH SPEED VACUUM CLEANER MOTOR
② AIR NOZZLE
③ ACCELERATING TUBE
④ LOUVER FOR "SPILLING" AIR
⑤ APERTURE FOR PARTICLES
⑥ CLOSED BOX
⑦ RANGED PARTICLE TRAJECTORY
⑧ VELVET OR REPLICA COLLECTOR
⑨ SIDE OF SNOW LABORATORY
NOTE: STANDARD OPERATING CONDITIONS PRODUCES AIR VELOCITY IN TUBE ③ OF 83 MI/HR

Fig. 13--Snow-particle apparatus

In order to evaluate the data obtained at Schenectady and summarized in Figure 15, weather maps from the Albany office of the United States Weather Bureau were obtained through the cooperation of E. J. Christie, chief of that office. These maps were the regular six-hourly plots and proved to be adequate for tracing the movement of anticyclones and fronts across the country and past the recording station at Schenectady.

Perhaps the most striking correlation is the increase of electrical activity upon the approach of a front. As the front reaches the station, its passage is generally indicated either by a cross-current snow storm or by a shift in sign of the air-to-Earth current. Of the 12 frontal passages shown on the maps covering the period January 9 to February 16, five were characterized by a shift of air-to-Earth current from positive to negative, two from negative to positive, and five were accompanied by cross-current storms having a duration of two to three hours. Such atmospheric electricity is perhaps to be expected in frontal systems because of the unusual convective air movements and active precipitation which often accompanies such air-mass movements. The passage of cold fronts is indicated in Figure 15 by a wedge-shaped figure whose point is located at the approximate time that the weather map shows the front passing Schenectady. The small-letter combinations on the Figure indicate the type of air mass above the station vicinity as indicated by the six-hourly maps. When a small arrow appears above these letters, it indicates the center of the air mass is near the station.

Other occurrences of abnormal amounts of atmospheric electricity shown on Figure 15 are not so easily accounted for as those just mentioned. A good example is the period between $16^{h}00^{m}$ January 18 to $16^{h}00^{m}$ January 19. The electrical effects in this period were considerably greater than were encountered in any of the positive-current snow storms observed during the winter. In this 24-hour period the skies were clear of any apparent clouds, although the atmosphere carried a considerable amount of haze and a thick ground fog covered the flat lands along the river during the night. During this period there was little wind on the ground or aloft. A study of the surface and upper-air maps does not reveal any obvious reason for this abnormal amount of atmospheric electricity. The only unusual feature observed is the fact that the station seemed to lie in a trough



Air velocity 83 mph, acceleration distance 32.5 cm

Precipitation code number	Range	l_1	l_2	t
	cm	cm	cm	cm
3	30	0.047	0.041	0.004
3	50	0.090	0.079	0.004
3	53	0.100	0.087	0.004
1	65	0.174	0.152	0.024
1	120	0.305	0.267	0.033
1	160	0.330	0.290	0.060
4	46	0.015	0.013	0.100
5	46	0.060	0.052	0.060
6	80	0.015	0.013	0.100
6	53	0.010	0.009	0.200
2	225	0.200	0.200	0.135
8	30	0.020	0.015	0.004
8	30	0.015	0.010	0.004
8	30	0.020	0.020	0.004
8	30	0.035	0.020	0.004
8	30	0.015	0.008	0.004

Fig. 14--Line drawings of snow particles with data on types whose range was determined by letting clumps of freshly-fallen dry snow enter the opening of the acceleration tube

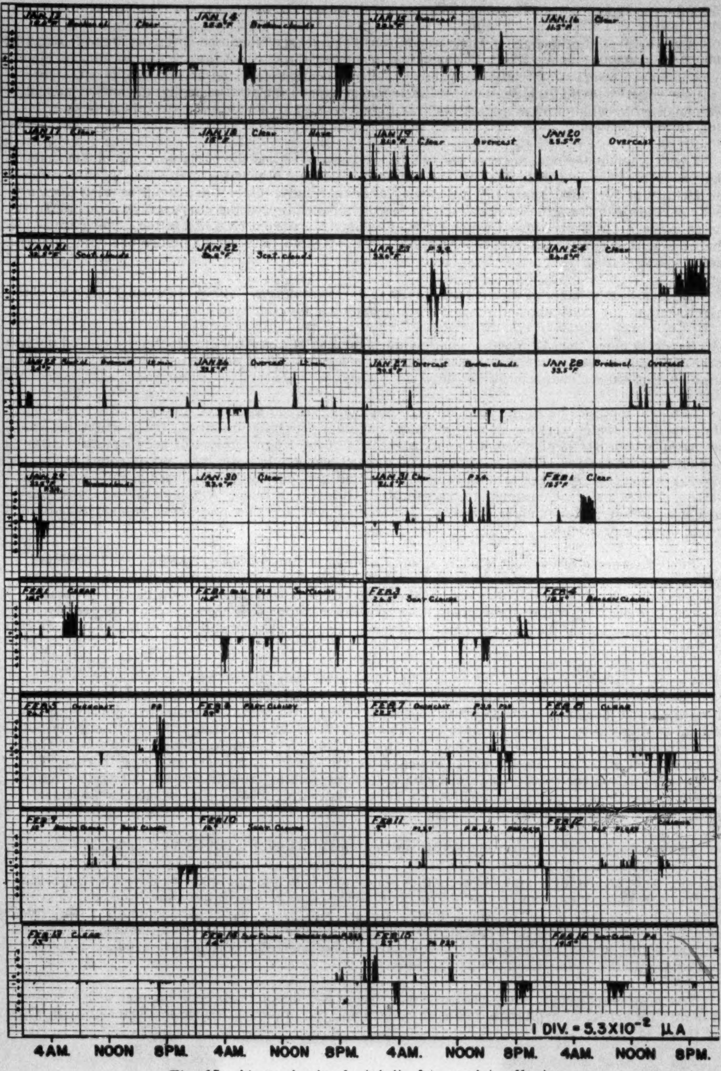


Fig. 15--Atmospheric electricity from point collector between a mass of continental polar warm air and some maritime polar air. This, of course, suggests the presence of a local front which had not developed to the extent that it was of importance.

Another period of unusual activity accompanied by nearly cloudless skies occurred January 24 17^h00^m to 02^h00^m January 25. In the morning preceding the current flow scattered cirrus clouds were observed which completely disappeared several hours before the activity occurred. The weather maps show that the center of an anticyclone passed the station during the active period accompanied by wind of 54 mph northwest at 10,000 feet. The surface wind at this time was 17 mph west-northwest.

Certain other periods, such as the evening of January 13 and the early morning of February 2, show negative currents with clear skies. In these cases and others the map shows precipitation in the vicinity of Syracuse, some 150 miles west of Schenectady. Since the prevailing wind during these periods was from the west and northwest, it is possible that the currents observed marked the passage of air parcels from which snow of a positive-current type had fallen. The negative charge remaining in the air might persist for a considerable time period before becoming neutralized.

Earlier in this paper reference was made to a "ghost storm" effect shown in Figure 6f which might account for these unusual currents of atmospheric electricity during clear weather.

Recently more than 12 months' continuous recording of atmospheric electricity picked up by a point collector was obtained at Schenectady. These records await detailed analysis but show the same kind of effects shown in Figure 15.

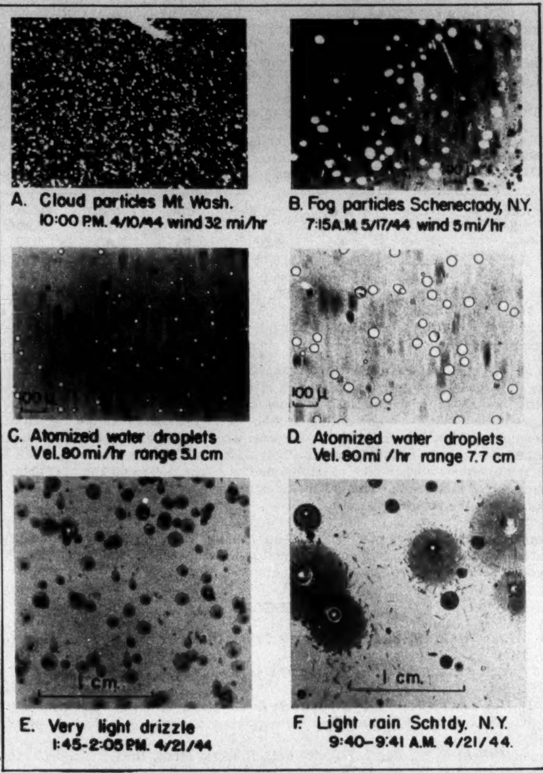
Methods for measuring the particle size of clouds, ground fog, mist, or rain--Early in the winter of 1943, while working on preliminary studies of precipitation static, the author tried various surface coatings in an attempt to obtain records of the fragmentation of snow crystals after they hit a solid surface at high velocity. The method previously described in this paper of making snow-crystal replicas of the broken crystals was finally used. Before using this rather obvious method, sooted and dyed coatings on the sampling slides were tried. Although these treatments were unsatisfactory for studying crystals, it was observed that they preserved an excellent record of liquid water droplets.

Further studies of the soot coating along conventional lines [STRAZHEVSKY, 1937] showed that the contact angle of a water drop on a sooted slide and the affinity of the soot for the glass base varied over wide limits. Because of these variables it was found to be difficult to obtain reproducible results. After some study it was discovered that soot coatings could be greatly improved in uniformity if the glass surface was made strongly hydrophobic before the soot layer was applied.

Various materials can be used to produce the initial hydrophobic coating to the glass slide. Such things as molten stearic acid, ferric stearate, or paraffin applied to the surface of a cleaned glass slide and thoroughly rubbed while hot with a clean cloth provide a satisfactory base for subsequent soot coatings. A more convenient and highly satisfactory coating can be obtained by putting a drop of silicone material, such as Drifilm No. 9987, on the slide (obtainable from the Resin and Insulation Materials Department, General Electric Company, Schenectady, New York). The drop is spread and the surface polished with a clean dry cloth. This treatment is carried out at ordinary room temperature and results in a permanently hydrophobic film of molecular dimensions.

After the slide is treated it should be cut into small pieces if used for measuring the particle size of clouds or other water droplets in the range of five to 50 microns. Squares about five mm on a side are a convenient size for sampling purposes. It is good practice to give a hydrophobic treatment to both sides of the glass microscope slide if it is to be cut into small pieces. Smaller pieces are necessary if the air speed is less than ten mph or the particles are smaller than five microns in diameter. The soot coating may be applied using a flame of city illuminating gas, propane, paraffin, or wax candle. If gas is used, the burner should be adjusted to produce a yellow flame. Any flame used should not produce visible smoke.

Trace micrographs to show what happens when water droplets come in contact with a sooted slide may be prepared by standard photomicrographic techniques as shown in Figure 16A, B, C, and D.



A. Cloud particles Mt Wash.
10:00 P.M. 4/10/44 wind 32 mi/hr

B. Fog particles Schenectady, N.Y.
7:15 A.M. 5/17/44 wind 5 mi/hr

C. Atomized water droplets
Vel. 80 mi/hr range 5.1 cm

D. Atomized water droplets
Vel. 80 mi/hr range 7.7 cm

E. Very light drizzle
1:45-2:05 P.M. 4/21/44

F. Light rain Schtdy. N.Y.
9:40-9:41 A.M. 4/21/44.

Fig. 16--Projection prints of traces of mist and rainfall made using sooted slides as negatives

With the larger traces such as are obtained with mist and rainfall the sooted slide may be used as a negative and projection prints made directly from it. The photographs shown in Figure 16E and F were made in this way. When this is done, the dark areas represent the regions where the soot has been removed by action of the water. Details of the rather complicated structure which appears with the larger drops will not be discussed here since they are not directly related to the problem at hand. It might be mentioned that experiment has shown that the lines radiating from the point of initial impact are caused by the escape of entrapped air from beneath the "mushroomed" droplet before the droplet draws back to its initial size.

Analysis of the relationships existing between the diameter of the soot traces and the droplets which produced them have been made in considerable detail. The relationship of the size of the trace is directly related to the velocity of impact of the droplet. With optimum conditions the diameter of the trace is a direct measurement of the particle size. STOKER [1946] has recently described a method to evaluate the traces produced on soot coatings taking into account the several variables which exist when sampling aerosols such as natural clouds. This method must be used caution, however, since the velocity of impact of the particles is affected to a considerable ee by the size and shape of the sooted plate. In order to determine the impingement velocity of the particles producing the tracks, it is necessary to know the trajectory of the particle as it approaches the sampling plate. The ranges of small particles in quiet air at several air velocities have been calculated by Irving Langmuir and are given in Table 8. The calculations show that many particles in the range of two to ten microns, having a speed of 20 mph, would not even reach the surface of a 1/4-inch or five-mm plate because of their short range.

Table 8--Ranges of small particles in quiet air at several air velocities

Diameter of H_2O droplets	Velocities of air					
	20 mph	40 mph	60 mph	80 mph	100 mph	200 mph
microns	mm	mm	mm	mm	mm	mm
2	0.114	0.212	0.302	0.385	0.470	0.830
6	0.90	1.64	2.30	2.86	3.40	5.72
12	5.82	9.50	13.05	16.0	18.7	28.9
24	11.4	19.60	26.0	31.6	36.2	54.7
40	28.4	46.8	60.70	72.3	82.1	119.0
100	135.0	206.0	257.0	298.0	332.0	439.0
200	413.0	595.0	720.0	810.0	880.0	1090.0

This "range effect" can be utilized for measuring particle sizes by constructing a sampling device similar in general principle to that shown in Figure 13, but on a miniature scale. The dimensions must be kept to the minimum size possible and an air velocity of at least 30 mph used. With higher speeds the device can be made somewhat large although it is not recommended that it exceed a dimension of 0.5 × 2.5-cm projected frontal area for an air speed of 200 mph. With such an apparatus the trace micrographs shown as Figure 16C and D were obtained. With this device it is only necessary to observe where the particles produce traces beyond the aperture. The diameter of the trace is not important. The unit besides being small should also have baffles to prevent turbulence within the ranging chamber.

Other methods for measuring cloud particles including water-sensitive dye coatings, molten vaseline, rotating multicylinders, and porous metal collectors that produce continuous automatic records have been studied and will be described elsewhere.

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MOVEMENT OF SEDIMENT AS BED LOAD IN RIVERS

A. A. Kalinske

Abstract--The movement of sediment which rolls and creeps along the bed of a river, and is known as bed load, is analyzed using basic physical principles of fluid dynamics. The conditions for the start of sand-grain movement are set down and form an important part of the analysis. The turbulence mechanism in the flow above the bed plays a most significant role in the analysis of rate of bed-load movement. The final equation developed for the rate of sediment transport is not empirical; all the numerical constants in it are definite physical measures either of the sediment or of the hydraulic and turbulence characteristics of the river. The equation fits laboratory and field data obtained for a wide variety of conditions by various experimenters.

Introduction--Hydraulic engineers have been concerned since the 18th Century with the calculation of the amount of sediment which rolls or creeps along the bottom of a stream, and a wide variety of empirical formulas have been developed from field and laboratory observations. This part of the sediment load of a river is known as bed load to distinguish it from the suspended load which is carried in the main body of the stream, the particles being kept in suspension by the turbulence. Whether the bed load or suspended load is the more important, or whether they are of equal importance, depends on the size of sediment entering a river and the hydraulic characteristics of the river; no general statements can be made. Analyses [see "References" at end of paper, KALINSKE, 1942] have indicated that transportation of sediment in water by the so-called saltation process is insignificant, and therefore need not be considered.

No attempt will be made to review the large amount of literature and data available on the subject of bed load; this has been adequately done by CHANG [1939] and JOHNSON [1943]. All the bed-load formulas available are more or less empirical, some are dimensionally inconsistent, and they are widely different in their form and in the variables present. Though many of these formulas have been very useful and quite good for certain conditions, their multiplicity has been very confusing and annoying to engineers attempting to calculate the transport of sediment as bed load. The ideas obtained from the sum total of all these past investigations, and especially the increase during recent years in the fundamental knowledge of turbulent fluid flow, now makes it possible to attack the problem of bed-load movement in a physically sound manner. It is, therefore, the purpose of this paper to derive expressions for bed-load movement theoretically, and to check such formulas by experimental data from as widely different sources as possible.

General concepts--The basic concept which must be considered in any analysis of movement of particles by a moving liquid, is that there is some minimum fluid force which will start a particle to move. Since even for unigranular material, all particles do not rest identically, this force will vary slightly for different particles, especially if the particles are quite angular. In any case the value of this force must be known and related to the unit boundary shear exerted by the moving liquid.

Another basic idea is that the force to which a particle is subject may not be constant, but instead fluctuates about some mean value. This fluctuation can be caused by two conditions: First, even though the general fluid motion is laminar, after certain critical flow conditions around a particle are reached small eddies are generated behind the particle, similar to those behind any blunt body, and these will cause the drag force acting on the particle to fluctuate. Secondly, the main fluid stream may be turbulent (as it usually is) and this relatively larger scale turbulence will cause the fluid velocity acting on any individual particle to vary considerably with time. How this turbulent fluid velocity varies must be known, or estimated, before any intelligent analysis can be made of bed-load movement.

The average rate of bed-load movement, by weight, will depend on the number and size of particles being moved and on the average speed with which they move. The determination of this average speed and its relation to the average hydraulic conditions of a river is one of the fundamental problems in this analysis.

The general idea of the important role that turbulence might play in any analysis of bed-load movement was first suggested to the writer by E. W. Lane, and he mentions this idea in his discussion of the paper by CHANG [1939]. EINSTEIN [1942] made an analysis which recognized the influence of turbulence on bed-load movement; however, he had to resort to dimensional considerations in order to obtain a consistent formula, and his physical picture is somewhat difficult to visualize.

Initial movement of particles--In a wide variety of sediment movement problems such as soil erosion, stable channels, and movement of material along beds of rivers, it is important that the flow conditions necessary to cause initial movement of any size of material be calculable. Expressions for the so-called critical velocity or critical drag (or shear) have been developed in the past; however, such equations were always concerned with mean values for turbulent flow conditions, and therefore the exact value of the critical force or velocity necessary to produce movement was not obtained. Thus, as will be shown later, the maximum force acting on a sand particle in the turbulent flow may easily be three or four times the mean value. However, whether the flow is turbulent or laminar, there is some minimum force which will cause a particle to be displaced and any analysis of the bed-load problem, if it is to be basically sound, must define that force.

Consider a particle of non-cohesive material resting on other particles, as is shown in Figure 1. The forces acting on it are those of gravity, bouyancy, and a fluid force, which will be approximately in the direction of flow. WHITE [1940] has shown that the lift or vertical force is quite negligible for conditions of bed-load movement, and that the exact location of the fluid force depends on the Reynolds number R_g of the grain which is defined as $v_x d/\nu$, where $v_x = \sqrt{\tau_0/\rho}$, τ_0 is the shear on the bottom, ν = fluid kinematic viscosity, and ρ = the fluid density. If this number is greater than 3.5 then the fluid forces acting normally on the particle are greater than the tangential and the resultant of the forces passes approximately through the center of gravity of the particle. The critical fluid force on a particle can then be expressed as

$$f_c = (\pi/6)\rho' g d^3 \tan\phi \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

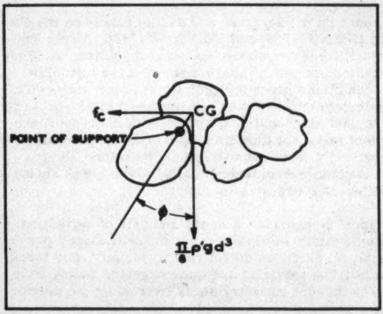

Fig. 1--Forces on sand grain

where $\rho' = (\rho_g - \rho)$, the effective particle density; d is grain diameter; and ϕ is the angle of repose of the sand grains. How this force acting on an individual grain is related to the bottom unit shear, τ_0, depends on the number of sand grains per unit area which are effective in taking the shear. This number depends on the closeness of packing of the grains which are lying on the top of the bed. Let this number be expressed as $p/(\pi d^2/4)$ where p is a factor which indicates the proportion of the bed taking the fluid shear. In general, the factor p should not vary greatly for unigranular material. The critical bottom shear is then equal to

$$\tau_c = \alpha p \rho' g d \tan\phi \quad \ldots\ldots\ldots\ldots (2)$$

The number α may not necessarily be 2/3, as theory indicates for a spherical grain, but will vary somewhat with particle shape. It should be remembered that for the moment only unigranular grains of approximately spherical shape are being considered; sand mixtures will be analyzed later on in the paper. If the Reynolds number, R_g, of the grain is greater than 3.5 the values of τ_c will be, according to data obtained by WHITE [1940], about half of that given by (2). This is because the turbulence produced in the wake of a grain causes the force to fluctuate, and evidently the maximum value reaches twice the mean force.

For R_g less than 3.5, White, using grains 0.20 and 0.90 mm, obtained a value of about 0.30 for αp. His direct determinations of p gave values of about 0.35 for ordinary unigranular sands. Most practical bed-load problems will be in the range of R_g values larger than 3.5. Since at present, only meager information is available regarding values of p and ϕ, the values given by White will be used as being close approximations for most sands. Therefore, the expression to be used in the remainder of this paper for critical tractive force, expressed in ft-lb-sec units, will be

$$\tau_c = 12d \qquad (3)$$

where $\tan\phi$ is taken as 1.0, $p = 0.35$, $\alpha = 2/3$, and $\rho' = (2.65 - 1)\ 62.4/32.2.$, and a factor 1/2 is introduced for the reason mentioned previously. This equation is for sand having a specific gravity of 2.65.

Equation 3 gives the actual critical tractive force that will start to move grains of diameter d; however, in turbulent flow, the maximum force may be considerably greater than the average value as calculated from the slope and depth of the river. To convert (3) so that τ_c is the mean critical tractive force, it is necessary to know how shear fluctuates about the mean value. Experimental data [KALINSKE, 1943] have indicated that the velocity fluctuation in turbulent flow near the bottom of rivers, is such that $\sigma/\bar{U}$ is about 1/4, where σ is the standard deviation of U about $\bar{U}$, and $\bar{U}$ is the mean velocity at a point. Also it has been demonstrated that the variation in U is in accordance to the normal error law. In that case, values of $(U - \bar{U})$ at times may reach 3σ, which means that the velcoity may reach magnitudes of 1.75 $\bar{U}$. Since shear varies as the square of the velocity, the shear at times may be $(1.75)^2$ or about three times the mean value. In that case, the critical mean shear need only be equal to 4d for movement to start. This agrees quite well with the empirical expressions derived by O'BRIEN and RINDLAUB [1934] from analysis of considerable data, and to SHIELDS [1936] experimental results.

Rate of material movement--To evaluate the average rate of movement of material along the bed, it is necessary to find the average speed of movement of the particles. Any single grain at any instant will have a velocity which will be equal to

$$U_g = b(U - U_c) \qquad (4)$$

where, U is the instantaneous fluid velocity at the grain level, and U_c is the critical fluid velocity. It seems that the factor b ought to be unity, and the writer's analysis of data on speed of pebble movement as obtained by KRUMBEIN [1942] indicates that this factor is, for all practical purposes, unity. Since U varies with time so will U_g; therefore, to obtain the mean speed of movement, it is necessary to find the mean value of U_g. If the number of unigranular particles per unit area are $p/(\pi d^2/4)$, then the mean rate of movement, by dry weight, per unit width of bed, is

$$G = [(\pi/6)\gamma_g d^3 \bar{U}_g][p/(\pi d^2/4)] \qquad (5)$$

or,

$$G = (2/3)dp\lambda_g \bar{U}_g \qquad (5a)$$

where γ_g is the specific weight of the material being moved, and $\bar{U}_g$ the mean speed of movement.

To evaluate $\bar{U}_g$, it is necessary to express the manner in which U varies and then find the mean value with respect to time of $(U - U_c)$ for all values of U larger than U_c. Statistically, it has been shown fairly definitely that U varies according to the normal error law, which is given as

$$f(U) = [e^{-(U - \bar{U})^2/2\sigma^2}]/\sqrt{2\pi\sigma} \qquad (6)$$

where, f(U) is the frequency function, and $\sigma = \sqrt{\overline{(U - \bar{U})^2}}$. The mean value of U_g will then be

$$\bar{\bar{U}}_g = \int_{U_c} (U - U_c)f(U)dU \qquad (7)$$

(The value of $\int_{-\infty}^{\infty} f(U)dU$ is unity). Let $(U - \bar{U})/\sigma = t$, and $(U_c - \bar{U})/\sigma = t_c$, there is then obtained after dividing $\bar{U}_g$ by $\bar{U}$ the following

$$U_g/U = (\sigma e^{-t_c^2/2}/U\sqrt{2\pi}) - (U_c/\bar{U} - 1)[1/2 - \int_0^{t_c} \phi(t)dt] \qquad (8)$$

where, $\phi(t) = e^{-t^2/2}/\sqrt{2\pi}$ and values of the integral can be obtained from tables. If $\sigma/\bar{U} = r$, then $t_c = (U_c/\bar{U} - 1)/r$, and it is noted that the ratio of $\bar{U}_g/\bar{U}$ is a function of the so-called relative intensity of the turbulence as given by r, and the ratio of U_c to $\bar{U}$. Since the shear varies as the square of the velocity, $U_c/\bar{U}$ can be written as $\sqrt{\tau_c/\tau_0}$, where τ_0 is the mean bottom shear. Note from the above expression that $\bar{U}_g$ will have a finite magnitude even though $U_c/\bar{U}$ is greater than 1.0, the magnitude of its value depending on r. If $r = 0$, that is, the flow is laminar, (8) reduces to

(4) where U is then replaced by $\bar{U}$. In Figure 2, values of $\bar{U}_g/\bar{U}$ are plotted against τ_c/τ_0 for values of r equal to 0 and 1/4. Note that the turbulence has no influence on values of $\bar{U}_g/\bar{U}$ for values of τ_c/τ_0 less than 1/2.

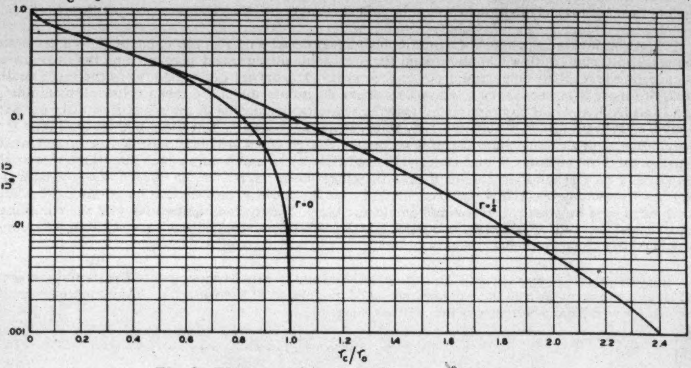

Fig. 2--Plotting of Equation (8) for r = 0 and r = 1/4

The equation for rate of bed-load movement can now be written in dimensionless form

$$G/\bar{U}d\gamma_g = (2p/3)(\bar{U}_g/\bar{U}) \quad \ldots \quad (9)$$

Since $\bar{U}$ is the mean fluid velocity at the grain level, boundary-layer theory indicates that it can be expressed as $c\sqrt{\tau_0/\rho}$, where the value of c is about 11. Letting p equal 0.35, (9) can be written as

$$G/v_x d\gamma_g = 2.5(\bar{U}_g/\bar{U}) \quad \ldots \quad (10)$$

or,

$$G/v_x d\gamma_g p = 7.3\,\theta\,(\tau_c/\tau_0) \quad \ldots \quad (10a)$$

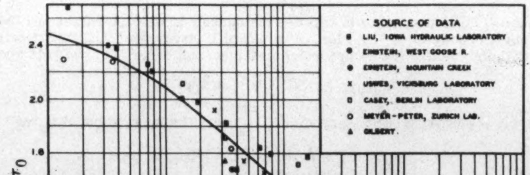

Fig. 3--Bed-load data; curve shown is Equation 10, p = 0.35

where, θ is the function of τ_c/τ_0 as indicated in Figure 2, and $v_x = \sqrt{\tau_0/\rho}$.

Equation 10a is the basic bed-load movement equation; however, it should hold strictly only for unigranular material of approximately spherical shape. Using (3) for τ_c and letting $r = 1/4$, (10) is plotted in Figure 3. Data as obtained from widely scattered sources are also shown in Figure 3. In some cases mean values of the data were used because of the great number of measurements that were obtained. In several instances, data for non-uniform sand have been plotted using the median diameter as the characteristic sand size. How (10a) applies to sand mixtures will be discussed in the following section. With data for small values of τ_c/τ_0, that is, when the bottom shear is high compared to the critical shear for bed-load movement, the measured values of G are considerably larger than the theory indicates. For such conditions it is very probable that there was suspended load movement and it is suspected that some of that load was measured in combination with the bed load. Under relatively high shear conditions it becomes difficult to measure just the bed load without, at the same time, trapping particles moving in suspension.

Application of theory to sand mixtures--For mixtures of graded sand, the critical conditions can be analyzed as follows: The factor p can still be considered as representing the portion of the bed area taking the shear, then p_i can be thought of as indicating the portion of the bed area covered by grains of d_i size. In that case $(p_1 + p_2 .... + p_i) = p$. The portion of the shear taken by grains of d_i diameter will be $\tau_0 p_i/p$ and thus the value of critical shear for any size particle will be

$$\tau_c = (2/3)p\rho' g d_i \tan \phi \ldots\ldots\ldots\ldots (11)$$

Thus, the value of τ_c/τ_0 for any given τ_0 will vary with particle size. Previous analysis have indicated that movement will be negligible when τ_c/τ_0 approaches three in value.

To evaluate the rate of bed-load movement when particles vary in size it is necessary to find the rate of movement of each of the different sizes, and then find the total rate by summation. To do this it is necessary to know the values of p_i for the different size grains. This can be determined from the size analysis curve which indicates the proportion present, by weight, of grains of different sizes. For graded sand mixtures it is best to subdivide the mixture into several size ranges, each of which can be characterized by the mean diameter of that range. Let n_i represent the proportion by weight of particles of size d_i. Remember that the factor p_i indicates the proportion of the bed area occupied by particles of size d_i. It can then be readily demonstrated that

$$p_i/p = m_i/m \ldots\ldots\ldots\ldots (12)$$

where $m_i = n_i/d_i$, and $m = (n_i/d_i + n_2/d_2 \ldots\ldots + n_i/d_i)$. Thus, knowing the factor p, which should not vary a great deal for ordinary sands, and having the usual size analysis data for the bed material, the factor p_i for the various size grains can be calculated by use of (12). By means of (10a) the value of rate of transport, G_i, for grains of size d_i can be calculated. The summation of these values will give the total rate of movement.

For any given sand mixture there is some grain size which, using (10), will give the same rate of movement as the summation process does. This size will not be constant for any given sand mixture but will vary somewhat with the value of τ_0. Several typical sand mixtures were analyzed in regard to this, and in general for approximate calculations the median diameter can be used without too much error.

Summary--The movement of sediment along the bed of a river or flume is analyzed theoretically in terms of the properties of the sediment grains and the hydraulic characteristics of the water flow. In the final expressions developed, certain of the numerical factors which were measures of the sediment properties and of the fluid turbulence had to be estimated from scanty data; however, the equations are free of empiricism and are physically sound and general in all respects.

In the increased knowledge of fluid turbulence that has become available in recent years is the significant material that permits this analysis of bed-load movement to be made. The complexities introduced into the bed-load movement phenomena by the action of the turbulence were undoubtedly the chief cause for the difficulties experienced in the past by bed-load movement experimenters in correlating and generalizing their laboratory data and field observations.

The essence of the present analysis is the breaking down of the problem into that of evaluation of the true critical tractive force for any size sand grain, and the development of a function of the ratio of critical tractive force to the mean force existing, which function characterizes the rate of bed-load movement for all flow conditions.

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A METHOD OF ESTIMATING SEDIMENT ACCUMULATION IN STOCK PONDS

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Abstract--To estimate sediment accumulation in 43 Government-owned stock-water ponds in central South Dakota, detailed sedimentation surveys were made on 18 representative ponds, and a multiple regression analysis was made to determine the function of various factors related directly or indirectly to sediment accumulation. The method provided a formula for estimating sediment accumulation in all ponds in the area.

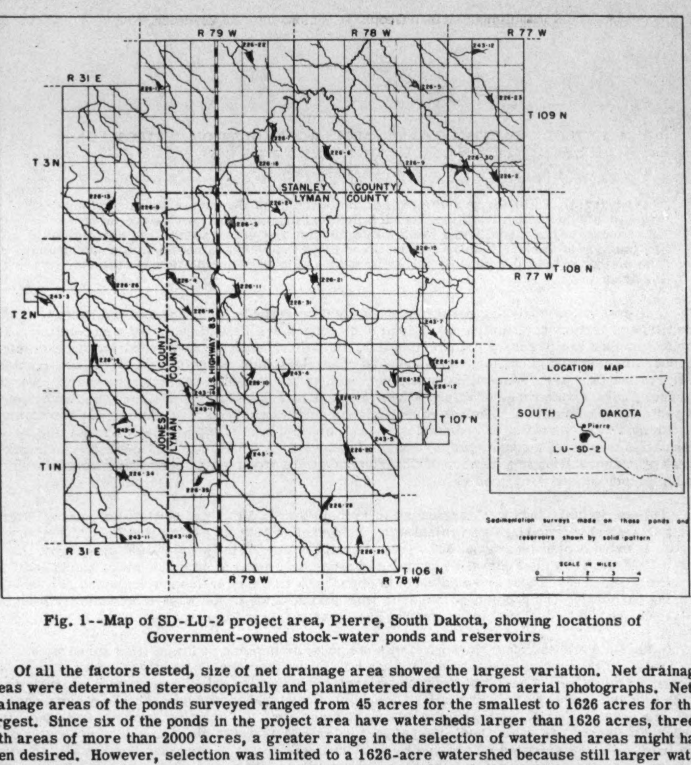
The problem of analyzing reservoir sedimentation records is highly involved because of the multitude of factors contributing directly or indirectly to the rate of sediment accumulation. These factors include age of reservoir, precipitation, size of net drainage area, capacity of reservoir, manner of reservoir operation, and watershed characteristics, including soil types, topographic features and land use. Some of these factors, such as the size of net drainage area and reservoir capacity, have a wide range of values which causes a correspondingly wide variation in the amount of sediment accumulation. The use of multiple correlation analysis to determine the function of the various factors related to sedimentation is a new approach to the problem of analyzing sedimentation data from a considerable number of reservoirs. The use of this method to estimate rates of sedimentation in a number of Government-owned stock-water ponds and reservoirs in South Dakota showed very good results.

This particular study was carried out in 1945 on the SD-LU-2 project located south of Pierre, South Dakota (see Fig. 1). This project was established in 1934 as part of the Federal relief program. It extends over an area of 327 sq mi of gently rolling to hilly and rough topography. Between 1936 and 1938 the Federal government constructed a total of 43 stock-water ponds and reservoirs in the area. These were adjuncts to community pastures which are leased to ranchers for grazing purposes. The problem arose as to what maintenance costs, caused by sedimentation in the ponds, should be included in the grazing fees chargeable to lessors.

In the time allotted for field work it was not possible to make sedimentation surveys on all of the ponds and reservoirs in the area. A study was made, therefore, of a variety of existing data in the project files, and of aerial photographs covering the area, to select representative ponds on which to make surveys. This preliminary study disclosed that topography, size of net drainage area, reservoir capacity, and, to some extent, land use were the principal variants from pond to pond and watershed to watershed. Hence, particular attention was given to selecting those reservoirs for survey which would provide representative sampling of these factors. In all, 18 ponds were selected and detailed sedimentation surveys made on these.

Of the more important factors related to sedimentation, soil characteristics, land use, and age showed the least effect on variation of sediment accumulation in this study. The soils are unusually uniform consisting of clays and clay loams of residual origin derived by weathering of Pierre shales. Land use is also fairly unifrom. The watersheds of all of the ponds and reservoirs are primarily well-grassed range land. The small amount of land in cultivation in the area is confined, generally, to level or gently rolling upland, and very little of the sediment derived from cultivated land reaches the ponds.

Although age of the ponds must necessarily be an important factor insofar as total sediment accumulation is concerned, its effect upon variation in sediment accumulation is small because most of the ponds were built about the same time. The age of the ponds varied from 6.7 to 9.3 years, a difference of only 2.6 years. Subsequent analysis of precipitation records indicated that several years elapsed after date of construction of the oldest ponds before any appreciable above-normal precipitation occurred during the erosion-producing months. As far as their sedimentation history is concerned, the ponds were nearly of the same age. Since all of these factors, soil characteristics, land use, and age are fairly uniform in the entire project area, they exert a more or less uniform influence on the rate of sediment accumulation and therefore do not have a great effect on variation of sediment accumulation.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LOCATION MAP
SOUTH DAKOTA
Pierre
LU-SD-2
Sedimentation surveys made on these ponds and reservoirs shown by solid pattern
SCALE IN MILES
0 1 2 3 4

Fig. 1--Map of SD-LU-2 project area, Pierre, South Dakota, showing locations of Government-owned stock-water ponds and reservoirs

Of all the factors tested, size of net drainage area showed the largest variation. Net drainage areas were determined stereoscopically and planimetered directly from aerial photographs. Net drainage areas of the ponds surveyed ranged from 45 acres for the smallest to 1626 acres for the largest. Since six of the ponds in the project area have watersheds larger than 1626 acres, three with areas of more than 2000 acres, a greater range in the selection of watershed areas might have been desired. However, selection was limited to a 1626-acre watershed because still larger watersheds contained as many as four or five privately owned stock ponds which had either been breached and repaired several times or their ages could not be determined accurately. Consequently, reliable data could not be obtained from these larger areas. Only one pond in the entire project area had a drainage area smaller than the smallest area of the ponds surveyed.

Original capacities of the ponds surveyed ranged from 2.6 to 44.3 ac ft. Of all the ponds in the area, six have original capacities greater than 44.3 ac ft but none smaller than 2.6 ac ft. Selection of ponds in the upper range of capacity was subject to the same limitation applicable to net drainage area.

Topography is difficult to measure and to express as a single quantity in a study of this kind. Because of the general uniformity of soils and geological features it was felt that topography was at least partially expressed in drainage density or the length of channelization per unit of drainage area. Drainage density of the ponds surveyed was determined stereoscopically and measured directly with a map measure from aerial photographs. The drainage density varied from a minimum of three feet per acre for a level to rolling watershed to a maximum of 89 feet per acre for a hilly to rough watershed. In general, drainage density was less than 30 feet per acre on very gently rolling to rolling topography, 30-65 feet on rolling to hilly topography and greater than 65 feet per acre on hilly to rough topography. Of the 18 watersheds above the ponds surveyed, six are located on gently rolling topography, five on rolling to hilly topography, and seven on hilly to rough topography.

Table 1--Summary of data on stock ponds and reservoirs, SD-LU-2 Project, Pierre, South Dakota

Project number	Topography	Drainage density	Net drainage area	Original capacity	Age to date of survey	Observed average annual	Estimated average annual[a]	Estimated average annual[b]
		ft/ac	ac	ac/ft	yrs	ac/ft	ac/ft	ac/ft
226- 1	Gently rolling	16.44	126	16.7	9.3	0.162	0.153	0.203
226- 2	Gently rolling	14.88	628	34.0	9.3	0.449	0.434	0.479
226- 3	. . . .	. . .	535	17.0	9.3	. . .	. . . .	0.328
226- 4	Hilly	77.49	475	13.6	9.2	0.400	0.325	0.286
226- 5	. . . .	. . . .	161	17.9	8.7	. . . .	. . . .	0.223
226- 6	Gently rolling	23.59	1626	31.8	9.3	0.724	0.730	0.762
226- 7	. . . .	. . . .	645	31.9	9.2	. . . .	. . . .	0.469
226- 8	. . . .	. . . .	502	19.7	9.2	. . . .	. . . .	0.338
226- 9	. . . .	. . . .	1022	37.2	9.0	. . . .	. . . .	0.620
226-10	. . . .	. . . .	360	19.9	9.2	. . . .	. . . .	0.297
226-11	. . . .	. . . .	1079	59.8	8.8	. . . .	. . . .	0.800
226-12	. . . .	. . . .	713	33.0	8.9	. . . .	. . . .	0.497
226-13	Hilly to rough	81.19	104	9.1	8.7	0.085	0.185	0.142
226-14	. . . .	. . . .	2239	216.7	8.8	. . . .	. . . .	2.277
226-15	. . . .	. . . .	1786	87.8	8.9	. . . .	. . . .	1.213
226-16	. . . .	. . . .	156	10.2	8.8	. . . .	. . . .	0.166
226-17	. . . .	. . . .	508	25.5	8.7	. . . .	. . . .	0.381
226-18	. . . .	. . . .	388	13.5	8.8	. . . .	. . . .	0.259
226-20	. . . .	. . . .	1361	73.2	8.7	. . . .	. . . .	0.981
226-21	Hilly	51.24	150	28.9	8.7	0.325	0.306	0.298
226-22	Very gently rolling	3.34	327	9.2	8.7	0.102	0.135	0.210
226-23	. . . .	. . . .	822	39.3	8.7	. . . .	. . . .	0.575
226-24	. . . .	. . . .	2348	98.0	8.7	. . . .	. . . .	1.455
226-25	Hilly	62.91	92	9.3	7.7	0.115	0.155	0.140
226-26	. . . .	. . . .	2411	150.0	8.1	. . . .	. . . .	1.849
226-28	. . . .	. . . .	457	30.3	8.6	. . . .	. . . .	0.401
226-30	. . . .	. . . .	1942	100.0	8.3	. . . .	. . . .	1.348
226-31	Rolling	38.23	141	13.9	8.3	0.189	0.168	0.188
226-32	Rolling	35.15	302	14.1	8.3	0.240	0.213	0.238
226-34	Hilly	39.29	774	44.3	8.1	0.535	0.594	0.597
226-35	Rolling	35.89	321	18.4	7.2	0.317	0.253	0.274
226-36	. . . .	. . . .	745	19.6	7.4	. . . .	. . . .	0.410
243- 1	Hilly	64.55	68	2.7	7.7	0.086	0.100	0.085
243- 2	Hilly to rough	89.47	84	5.2	7.7	0.289	0.161	0.108
243- 3	. . . .	. . . .	178	4.0	7.7	. . . .	. . . .	0.128
243- 4	. . . .	. . . .	164	3.1	7.7	. . . .	. . . .	0.117
243- 5	Hilly	62.14	45	2.6	7.7	0.049	0.088	0.078
243- 6	Hilly	86.13	74	3.2	7.7	0.055	0.138	0.091
243- 7	. . . .	. . . .	244	5.0	7.3	. . . .	. . . .	0.155
243-10	Gently rolling	14.50	340	3.7	7.1	0.118	0.114	0.174
243-11	Gently rolling	17.87	216	4.5	7.0	0.090	0.088	0.143
243-12	. . . .	. . . .	26	8.2	7.3	. . . .	. . . .	0.112
243-14	. . . .	. . . .	786	13.0	6.7	. . . .	. . . .	0.375

[a] Calculated with formula $S = 0.0077C + 0.0003A + 0.0015D - 0.0385$. [b] Calculated with formula $S = 0.0072C + 0.0003A + 0.0454$.

Analysis of data consisted of both multiple linear regressions and curvilinear regressions including the compound discount formula which reasoning indicated might explain rates of sediment accumulations in reservoirs. As a result of these analyses it was found that sediment accumulation in the ponds, based on the 18 surveys, could be expressed best by the linear formula

$$s = 0.0077C + 0.0003A + 0.0015D - 0.0385 \dots\dots\dots\dots\dots\dots (1)$$

where s is annual sediment accumulation, in ac ft; C is capacity of the pond in ac ft; A is net drainage area in ac; and D is drainage density in ft per ac. The above formula accounts for 91 per cent of the variations in annual sediment accumulation as expressed by the standard deviation.

The analysis was extended to test the above factors, and others, individually and in combination with each other in order to obtain a satisfactory formula which did not include drainage density, for the measurement of this factor involves considerable work. Original capacity and net drainage area gave the best-fitting formula of those from which drainage density was omitted. This formula, $s = 0.0072C + 0.0003A + 0.0454$, accounts for 87 per cent of the variance in sediment accumulation as expressed by the standard deviation. Since the values of C and A were readily available from existing data and since the fit is still satisfactory, this formula was used to compute the estimated rate of silting of all ponds in the area. The agreement between observed values and calculated values is shown in Table 1.

It might be of interest to point out briefly how the results of this analysis were applied. Damage by sedimentation in a stock pond becomes critical when sediment encroaches upon the dependable water supply or the storage needed during the grazing season to offset cumulative losses by seepage, evaporation, and stock consumption. Any storage capacity in excess of the dependable storage capacity could be silted up before effects of sedimentation would become critical. There were two types of ponds built in the area. The larger ones, or so-called reservoirs, were designed for more or less permanent use. To supplement these reservoirs, smaller ponds were built comparable to privately-owned stock ponds in the area. These smaller ponds have a life expectancy of about 25 years in this region. In the absence of previous studies in this area, the dependable water supply was arbitrarily chosen as one which will not fail more often than once in 15 years for the reservoirs and more than once in five years for the stock ponds. The dependable storage capacity was computed by the formula

$$C_d = RA + a(P-E-S) - U \dots\dots\dots\dots\dots\dots (2)$$

where C_d is dependable storage capacity in ac ft, R is runoff during grazing season from net drainage area in ac ft per ac, A is net drainage area in ac, E is evaporation from pond surface in ac ft per ac; S is seepage from pond in ac ft per ac, P is precipitation in ac ft per ac, a is surface area of the pond in ac, and U is amount of water used by livestock, in ac ft.

The difference between the dependable storage capacity and the total capacity of a pond is the amount of storage in excess of the dependable storage.

Using the average annual rate of sediment accumulation as estimated by the multiple regression equation, the expected life of excess storage of each pond was estimated and this figure used as a basis for computing damages resulting from sedimentation. This is based on the assumption that the average annual rate of sedimentation of each pond will continue as a constant throughout the life of the excess storage capacity. Studies of reservoir sedimentation in other sections of the country indicate that the trap efficiency of a reservoir decreases as sediment accumulation increases. Consequently, the mean annual rate of sedimentation becomes less as the reservoir becomes older, all other factors being equal. This was not determinable by the multiple regression analysis because the ages of the ponds are so nearly the same. If the trap efficiency of the ponds will be reduced within the life of the excess storage capacity, then sedimentation of the ponds will progress at a lower rate than that calculated by the regression formula.

A multiple regression analysis is a convenient method of simplification of a mass of complex data. Good results were obtained in this particular study, but it must be remembered that the functions developed are applicable only to this area where values of various factors are within the range of those determined by the surveys. In another area where soils, land use, precipitation, age, and other factors vary considerably and, consequently, may exert a different influence on sedimentation, a similar sample survey must be made and an analogous function fitted to the data. A criterion of the goodness of fit secured for any set of data is a by-product of the fitting process.

Acknowledgments--Assistance and guidance in making the multiple regression analysis was given by A. E. Brandt, Research Specialist in Experimental Design and Analysis, and Henry Hopp, Soil Conservationist, Office of Research, Soil Conservation Service, Washington, D. C. For method used see "Correlation and Machine Calculation," by H. A. Wallace and George W. Snedecor, Iowa State College of Agriculture and Mechanic Arts, Official Publication, v. 30, no. 4, 71 pp., June 24, 1931.

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BOUDINAGE

Ernst Cloos

Introduction--A "Boudin" is a sausage, and boudinage is a sausage structure. The term was coined by LOHEST [see "References" at end of paper, 1909] for a peculiar structure in certain sandstone beds in the Bastogne in Belgium.

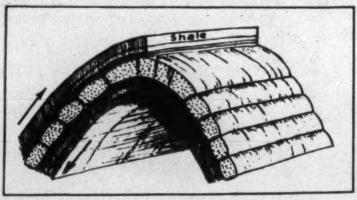

Fig. 1--Fold with quarzite bed between shaly layers. The former is broken into fragments by tension joints which are filled with quartz veins; arrows indicate relative movement

The sandstone beds are segmented and the segments are separated from each other by quartz veins. Each part is thickened in the center and appears in cross section almost like a barrel. The tops and bottoms of these barrels form the quartz veins. Looking at the bedding plane one sees enormous cylinders or boudins side by side (see Figs. 1, 4, and 11).

F. CORIN [1932] described other examples of boudinage and suggested that these sausage-like bodies are caused by folding and deformation. Several authors contributed to the discussion but few thought of boudinage as an important structure. In America only one paper [QUIRKE, 1923] seems to carry the term boudinage in the title and the author has found no reference to it in any textbook on structural geology and it seems that with few exceptions it has escaped notice.

It is the purpose of this paper to call attention to this rather common feature and to point to its application in structural geology.

Historical review--Several observers have described swelling and thinning of beds or veins and ascribe these to folding, compression, or consider them as primary irregularities. For instance, RAMSAY [1866] may have noticed the structure, "In the great quarry west of the Ffestiniog and Trawsfynydd fault the cleavage dips from 45 to 50° northwest, the inclination of the beds being about 35° in the same direction and a greenstone dyke runs through them between the cleavage planes...bulging and thinning off in a rapid succession of oval-shaped masses three or four feet in length. Associated with it are quartz veins occurring principally at the points between the separate bulgings of greenstone" [WALLS, 1937, p. 325].

HARKER [1889] wrote a note on thickening of dikes and beds by folding and his illustration seems to indicate that he was aware of the problem. Renard called the quartz veins between individual boudins "filons primaires" and assumed the structure to be formed at the bottom of the sea after sedimentation.

REYER [1892] describes folding and boudinage in the limbs of the anticlines due to elongation in a down-dip direction. He does not use a special term for the phenomenon.

LOHEST [1909] calls attention to observations and descriptions by Renard. He shows, however, that the quartz veins contain tourmaline and garnet and are therefore not of primary but later origin. Figure 3 shows relation of cleavage, bedding, and boudinage after Lohest.

SEDERHOLM [1911] shows boudinage in the description of the Tammersfors quadrangle, Finland (see Fig. 7) but does not use the term. A granite dike is broken and its parts are pulled apart, the fracture is filled with quartz which, however, does not penetrate the schist which has a tendency to move into the fracture.

A similar structure is shown by BALK [1927, Fig. 29]. A norite dike has been stretched in the direction of distention. The fractures are, however, not filled with quartz veins but gneiss that has been sufficiently plastic to flow into the gaps (see Figs. 8 and 9).

Veins or dikes lend themselves to boudinage during subsequent deformation as is shown in an excellent example by HOLMQUIST [1930]. A skarn layer has been drawn far apart and the fractures between fragments are partially filled with quartz. The surrounding leptites are also drawn in and help fill the gaps (see Fig. 6).

QUIRKE [1923] discussed boudinage and felt that it is unusual. His drawings illustrate the phenomenon (see Fig. 4) and his interpretation of it (see Fig. 5). He ascribes the barrel shaped boudins to compression in the bedding plane and modification of their form by elastic reaction to release of load.

WEGMANN [1932] and CORIN [1932] both discussed boudinage from the classical localities in Belgium and added examples in granitized terranes. Figure 14 is traced from a photograph by Corin, and Figure 19 shows the development of boudins in granitized terranes after Wegmann. These authors agree on a mechanism for the formation of the structure as due to stretching or elongation of a competent between incompetent beds. Wegmann (see Fig. 19) shows how the barrel shaped boudins may be deformed into entirely disconnected lenticular pebbles in extremely mobile areas. Quirke's idea of compression in the direction of bedding is rejected.

READ [1934] calls attention to the structure and summarizes the situation in an excellent illustration (see Fig. 11) which shows steeply dipping boudins.

WALLS [1937] records boudinage from Scotland (see Fig. 12).

A few recent papers in America have called attention to boudinage. WATERS and KRAUSKOPF [1941] list it as one of the structures present but without particular description or illustration. GAULT [1945] illustrates boudinage in granodiorite. Inclusions are fractured and pulled apart as in the dike shown by Balk.

The author has called attention to a case of boudinage in the Martic area, Lancaster County, Pennsylvania (see Fig. 20) where a thick bed of edgewise conglomerate has been broken into almost square blocks. These were then rotated clockwise so that the longest diagonal is now in the direction of bedding. Between the blocks are pegmatites, calcite, or quartz veins and the shale above and below has flowed into the area between the blocks [CLOOS and HIETANEN, 1941].

In a recent paper dealing with lineation, the author called attention to boudinage and illustrated it (see Fig. 13) [CLOOS, 1946].

Boudinage appears here and there in the literature mostly incidental to other observations. The majority of authors agree that it is caused by elongation and extension of competent between incompetent beds.

Other examples of boudinage--Boudins appear to form independent of composition or kind of materials as long as there is a difference between competency of beds involved and definite layering. A dike in granite, quartzite between shale beds, dolomite layers between shale or limestone, or greenstone between volcanic ash, all may produce similar structures.

Figure 13 shows a quartzite bed between layers of Wissahickon schist [after CLOOS, 1946, p. 17]. The quartzite bed is torn by joints which are perpendicular to bedding and parallel the fold axis. These fractures are also normal to the dip of the beds and to elongation down dip. The edges of the bed at the fractures were rounded off and the bed appears lenticular in cross section. Cleavage is at a large angle to bedding and the shaly layers have filled the gaps. There seems to be little doubt that boudinage is here caused by elongation down dip of the limb of the fold.

A dolomite bed is bent along a fault zone in Figure 15. Fractures formed normal to the bedding and are filled with quartz veins. The edges of the blocks are not rounded and one may consider this example as the beginning of boudinage.

Figure 17 shows a sandy bed between shaly layers where the competent layer is drawn out much as in the case of the quartzite described above. The incompetent layers flow into the gaps and thicken. Only the adjacent layers are affected, a few feet from the boudin layers are undisturbed (see also Fig. 20).

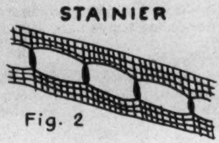

Fig. 2

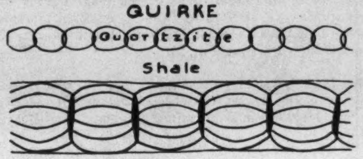

Fig. 4

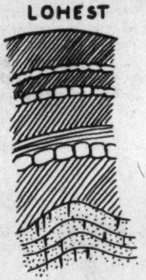

Fig. 3

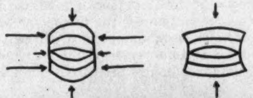

Fig. 5

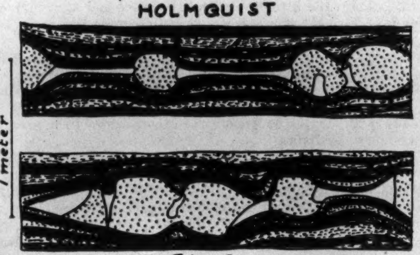

Fig. 6

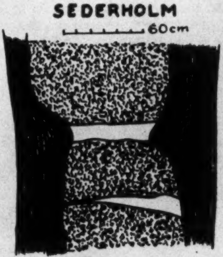

Fig. 7

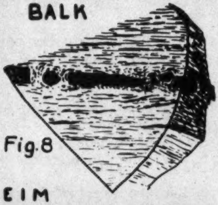

Fig. 8

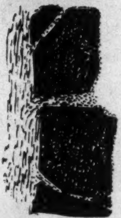

Fig. 9

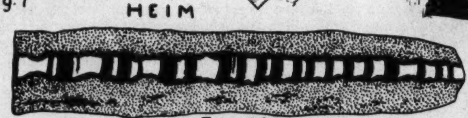

Fig. 10

Fig. 2--Boudinage after STAINIER [1907]; Fig. 3--Boudinage in quartzite (white) in a fold, cleavage in shale beds is at an angle to bedding, after LOHEST [1909]; Fig. 4--Schematic drawing of boudinage after QUIRKE [1923], black vein of quartz; Fig. 5--Explanation of thickening of boudins by lateral compression and release of elastic deformation, after QUIRKE [1923]; Fig. 6--Ladder vein in leptite, dotted areas are skarn rocks, white are quartz veins, dark are banded leptite, after HOLMQUIST [1931]; Fig. 7--Porphyry dike is fractured and the schist drawn into the gap which is filled with quartz, after SEDERHOLM [1911]; Fig. 8--Norite dike in gneiss, extended in the direction of stretching gaps are filled by gneiss, after BALK [1927]; Fig. 9--Norite dike extended and traversed by several apophyses of gneiss, after BALK [1927]; Fig. 10--Stretched belemnite in shale with white partitions filled with calcite, after ALBERT HEIM [1921]

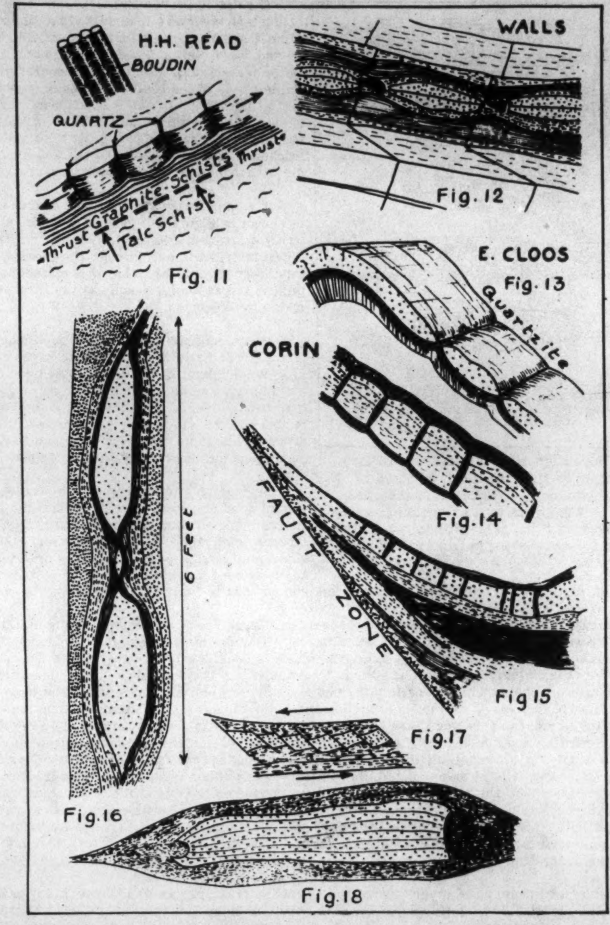
H.H. READ
BOUDIN
QUARTZ
Thrust
Graphite Schists
Thrust
Talc Schist
Fig. 11
WALLS
Fig. 12
E. CLOOS
Fig. 13
Quartzite
CORIN
Fig. 14
FAULT ZONE
Fig 15
6 Feet
Fig.16
Fig.17
Fig.18

Fig. 11--"Schematic representation of the boudinage structure at the Taig, Nor Wick, Unst", after H. H. READ [1934]; Fig. 12--Quartzite boudins (dotted) separated by quartz veins in matrix of fine siltstone, after WALLS [1937]; Fig. 13--Quartzite bed in Wissahickon schist is partitioned into boudins on the limb of a fold, after E. CLOOS [1946]; Fig. 14--Classical boudins in Bastogne, drawn from a photograph by F. CORIN [1932]; sandstone is dotted, quartz partitions are black; Fig. 15--Dolomite bed (dotted) is bent on fault zone and fractured into prospective boudins, fractures are filled by quartz, Safe Harbor, Pennsylvania; Fig. 16--Dolomite bed is drawn out in the direction of elongation in limestone, Howellville quarry, N. E. of Paoli, Pennsylvania; Fig. 17--Small sandy bed broken and fragments tilted in the direction of relative displacement, Antietam battlefields, Washington County, Maryland; Fig. 18--Large boudin of quartzite in gneiss, note the curving ends

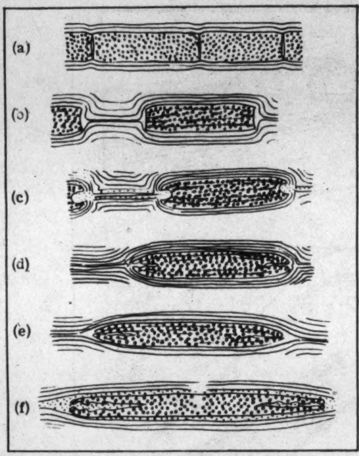

Fig. 19--Boudinage after WEGMANN [1932]: (a) Classical stage (Lohest, Read); (b) Beds of differing resistance; (c) Boudinage in granitized terranes; (d) The ends of (c) are almost entirely turned in; (e) Final stage withoug pegmatization; (f) Far advanced stage from highly mobilized terrane

If relative movements on either side of the competent layer are intense and the blocks are almost square, rotation may occur as in Figures 17 and 20. Rotation in Figure 20 is at a rather large scale and resulted in an unconformity at the left side of the block and a conformable contact at the right. In small exposures, such unconformity may prove to be rather misleading particularly since the overlying beds are also thickened toward the left and the picture of a major unconformity is almost perfect.

A rather irregular boudin of quartz in gneiss is shown in Figure 18. The original layer is entirely disrupted, fragments are not in a layer but irregularly scattered through the gneiss; the turned-in edge of the original fragment is rather typical and resembles some of the examples shown by Wegmann.

Many examples of excellent boudinage occur below Great Falls in the Potomac River gorge near Washington, D. C. Here shaly beds are metamorphosed and have become more competent than sandy layers. The beds are completely disrupted and the sandy layers "intruded" the gaps. Strings of boudins many feet long can be observed at many points especially on Bear Island.

Discussion and interpretation--Interpretation of boudinage will have to explain the formation of initial fractures, their filling, their relation to cleavage, the barrel shape of boudins, rotation of boudins, and thickening or thinning of adjacent beds without disturbance of beds a few feet distant, or in other words, restriction of the phenomenon to individual layers.

The initial fractures are tension joints normal to a direction of extension. In Figure 21 three beds are shown (a) before folding and (b) after folding. During this process the beds have slipped over each other and the line AB has become AB′ which is considerably longer. Since the competent bed does not yield by flowage, it adjusts by fracturing. The fractures are perpendicular to that component of tension which parallels the bed and slippage plane. The incompetent beds above and below are, in this case, able to yield by flowage in the direction of maximum extension of line AB into AB′. Normal to this line there is shortening and in that direction flowage may result in mineral orientation and subsequent cleavage. The angle between cleavage and bedding depends on the amount of folding, flowage, and the physical properties of the incompetent layers. This cleavage is fan-shaped as it is in many such folds. Slippage of the beds tends to open the fractures in the competent layer and the minerals which fill them depend on the availability of quartz, calcite, or others. Since fractures are restricted to the competent layer, mineral veins do not penetrate the adjacent soft layers. The sliding of beds past each other discourages continuation of the fractures and may tend to result in drag of cleavage along bedding surfaces. Such drag is common and has been described.

Thickening of incompetent layers above and below the fractures as in Figures 7, 16, or 20 may be explained by migration of softer material in the bedding plane during slippage. The fractures are weak areas in the beds and extension in AB′ will also tend to favor flowage of material into the gap. If adjacent beds, as for instance the limestone conglomerate in Figure 20, are separated by a slippage plane from the beds below, another set of conditions will there arise and migration of material in the lower layers will not affect those above. Boudinage is restricted to those groups of layers in which the physical properties and movements are favorable.

Rotation of boudins is unlikely if their cross sections are much elongated as in many of the figures shown but becomes more probable if the cross section approaches a square, where the distance between fractures is nearly equal to the thickness of the bed. If in addition viscosity is sufficient to create drag due to friction, rotation becomes unavoidable.

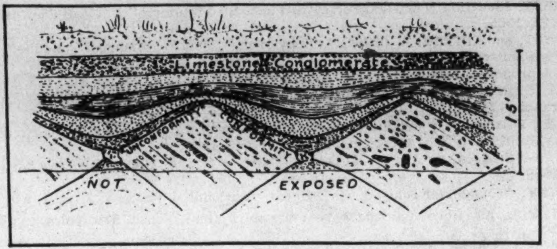

Fig. 20--Boudinage in edgewise conglomerate bed; Conococheague limestone, south of Mt. Hope Church, Pequea Creek, Lancaster County, Pennsylvania

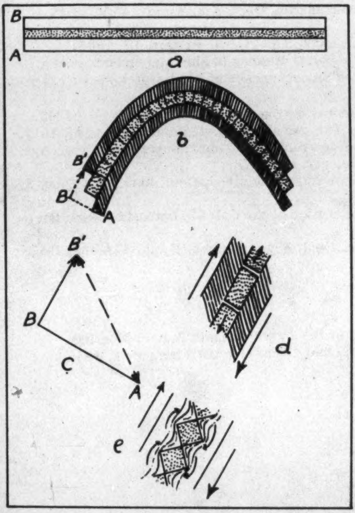

Fig. 21--Relative movement between beds caused by flexure folding: (a) Pre-deformation stage; (b) Folding results in elongation of AB to AB', and slippage between beds as indicated in (d); (c) Enlargement to show components AB'; (d) Relative movement as indicated by arrows results in tension fractures normal to bedding planes; the blocks begin to separate; (e) Rotation of square blocks caused by slippage of layers

The barrel shape of the classical boudins is somewhat puzzling but seems to be a function of incipient flowage in the competent layer. Wegmann (see Fig. 19) shows several stages of deformation in granitized terranes. Boudins may retain the terminal cavities because they are apt to be mineralized as in Figure 19, (c), (d), and (f). The author has observed similar stages in limestone boudins at many localities.

Boudinage is not restricted to gently folded beds but is also common in granitized areas as described by Wegmann particularly from Finland or as shown by Holmquist (see Fig. 6). It may appear in any complex where a competent layer is between incompetent ones.

The variety of forms in boudinage is astonishing and invites speculation and analysis. Many different forms seem to result from application of one mechanical principle. Observations on boudinage are scattered and unsystematic but much information may be unearthed if attention is called to it.

Boudinage permits determination of direction of extension and relative movement. It may furnish data on the amount of displacement in many instances. The degree of relative competency or incompetency may be determined by observation of rotation of boudins or their distortion. Investigation of mineralization of veins between boudins may furnish clues on the conditions of crystallization at the time of deformation. Other applications may appear with accumulation of evidence. It would seem that systematic observation and analysis of the phenomenon may contribute valuable information to the analysis of rock deformation.

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Transactions, American Geophysical Union Volume 28, Number 4 August 1947

EARTHQUAKE STUDY IN SOUTHERN CALIFORNIA, 1946

B. Gutenberg and C. F. Richter

(Contribution No. 405, Balch Graduate School of the Geological Sciences)

This continues the previous report [see "References" at end of paper, GUTENBERG and RICHTER, 1946a].

Data from the New Mexico atomic bomb test of 1945 have been published by GUTENBERG [1946], and those from the second Bikini test by GUTENBERG and RICHTER [1946b]. For both tests the travel times of P are within about two seconds of those calculated from the standard travel times of earthquake waves as corrected for a surface focus. The seismograms are very small; there is no basis for the exaggerated newpaper sensation, nor for the suggestion that seismograms might be used to detect such atomic bombs. Air waves from the New Mexico test included direct waves, refracted waves through the stratosphere, and strong waves traveling near the tropopause with little loss of energy.

Research in connection with the Navy's microseism project has led to a further publication by GUTENBERG [1947]. It appears that a large fraction of the energy in microseisms associated with hurricanes is transmitted from the surface to the bottom of the ocean by elastic waves. Vertical geological discontinuities interfere with the propagation of microseisms to a distance.

The revised study of the seismicity of the earth has been completed, and will be published in book form.

S. T. Martner has prepared a paper on the Dominguez Hills earthquakes of June 18, 1944.

A study of travel times at distances from 05° to 25°, particularly with reference to minor observed waves and to the structure of the crust, is being undertaken by Gutenberg.

The theoretically expected phase PKKKP has been tentatively identified on seismograms of the Central American earthquake of January 26, 1947. Preliminary epicenter and origin time are assigned by the United States Coast and Geodetic Survey as follows: 13°N, 86°.5W, $0 = 10^h06.7^m$.

Readings attributed to PKKKP are: Pasadena, $10^h55^m57^s$; Mt. Wilson, $10^h55^m56^s$; Riverside, $10^h55^m49^s$; Palomar, $10^h55^m51^s$; and Tucson (courtesy, U. S. C. and G. S.) $10^h55^m25^s$.

Isolated instances of this sort have been noticed before. The Alaskan earthquake of May 4, 1934, with epicenter at 61° 1/4 N, 147° 1/2 W, origin time $04^h36^m07^s$, and depth 80 km, produced a small wave at Pasadena at $05^h24^m44^s$.

A group of small shocks near Pomona, probably associated with the minor San Jose fault, is being investigated by Richter and Martner.

Routine bulletins for teleseisms and local shocks have been issued through the third quarter of 1946.

The most important shocks in the Southern California area during 1946 were the Walker Pass earthquake of March 15 (noted in the previous report), a shock of magnitude 5.6 on July 18 in the central Mojave Desert, and one of magnitude 5.0 on September 27, on the San Andreas fault in San Gorgonio Pass. The second of these is the largest Mojave Desert shock in twenty years of recording at Pasadena. (A larger one occurred on April 10, 1947.)

The great earthquakes shown in Table 1 (magnitude 7 3/4 and over) occurred during the year.

Table 1--Great earthquakes of 1946 (magnitude 7 3/4 and over) (preliminary determination)

Date	Time	Latitude	Longitude	Magnitude
	h m s	°	°	
August 4	17 51 05	19 1/4 N	69 W	8.1
September 12[a]	15 20 20	23 1/2 N	96 E	7 3/4
September 29	03 01 55	4 1/2 S	153 1/2 E	7 3/4
December 20	19 19 05	32 1/2 N	134 E	8.2

[a] Second of two shocks, three minutes apart.

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NOTES AND PERSONALIA

NOTES

Corrigenda--The following corrections are noted in the Transactions:

Vol. 28, no. 1, February, 1947, p. 152, note on new magazine concerning the Pacific. The note incorrectly states that E. H. Bramhall is Editor-in-Chief. A. Grove Day is Editor-in-Chief. Bramhall is a member of the Editorial Board.

Vol. 28, no. 2, April, 1947, p. 156 in paper by Walter D. Lambert on Deflections of the vertical from gravity anomalies. In the second last line of the paper, the value 0.01 should read 0°.01; that is, one one-hundredth of a degree.

School of Cosmic Physics in Dublin--Annoucement has been made of a School of Cosmic Physics as the third constituent school of the Dublin Institute for Advanced Studies. John J. Nolan, Professor of Experimental Physics, University College, Dublin, has been appointed Chairman of the Governing Body. L. W. Pollak, H. A. Brück, and L. Janossy have been appointed as Senior Professors, with Professor Pollak as Director.

Marine Seismic Prospecting--A recent issue of Nature (May 24, 1947, p. 707), carries a brief account of seismic prospecting in water at depths greater than 100 fathoms. The method of placing the charge on the bottom, as for lesser depths, was varied by placing the charge at a known depth, and placing hydrophones at various locations, including on the bottom. The records indicate that the seismic waves are transmitted from the bottom into the water satisfactorily.

Reprinting of Volume VIII, Physics of the Earth Series (Terrestrial Magnetism and Electricity)--Arrangements are being made by the National Research Council for the reprinting of Terrestrial Magnetism and Electricity, Volume VIII of the Physics of the Earth Series. Inquiries concerning this should be addressed to R. C. Gibbs, National Research Council, Washington 25, D. C.

Aerial Photography Status Map--The U. S. Geological Survey has recently released the second edition of their map showing the status of aerial photographic work. Copies are available upon request to the Map Information Office of the Survey.

Committee on UNESCO of the National Research Council--The National Research Council has organized a Committee on UNESCO under the Chairmanship of Bart J. Bok of Harvard. The Committee has established a six-point program of action, as follows: (1) To act as a clearing house for suggestions about UNESCO activities submitted by American scientists; (2) to act upon requests for advice and assistance received from the Natural Sciences Division in Paris and from the Field Science Cooperation Offices; (3) to assist the members of the U. S. National Committee; (4) to foster participation by American scientists in the affairs of UNESCO and to give wide publicity to the activities of UNESCO, especially in the field of the Natural Sciences; (5) to promote exchanges of scientists under the auspices of UNESCO; and (6) to utilize the facilities of UNESCO in the advancement of science. The Committee is now issuing a bulletin, copies of which may be secured through the National Research Council, to aid in the fulfillment of this program.

Second International Conference on Soil Mechanics and Foundation Engineering--The second International Conference on Soil Mechanics and Foundation Engineering will be held in Rotterdam, Holland in June 1948, under the sponsorship of the Netherlands Government. Information regarding the details of the Conference may be secured through the Office of the U. S. National Committee on Soil Mechanics, The Technological Institute, Northwestern University, Evanston, Illinois.

New uses for hydrostatic tube--It has been suggested by R. B. Montgomery, writing in Nature (March 22, 1947), that a submarine tube, filled with water, can be used to determine the true difference in elevation of points in a flowing stream, such as (he suggests) the Gulf Stream in the Straits of Florida. He points out that the method was developed by N. E. Norlund of the Danish Geodetic Institute. It is pointed out that, if the ends of the tube are miles apart, correction would have to be made for differences in temperature and barometric pressure.

Lectures on climatic fluctuations-- A series of three special lectures on Glaciology and Meteorological Evidences of the Present Climatic Fluctuations was presented by Hans W. Ahlmann, Institute of Geography of the University of Stockholm in Washington, D. C. in June, under the sponsorship of the U. S. Weather Bureau.

Earthquakes, February to June, 1947--E. Peterschmitt of the Institut de Physique du Globe, Strasbourg, France, reported that an earthquake recorded by the seismographs at $00^{h}13^{m}33.0^{s}$ U. T. on February 17 had an S-P distance of 450 km. The earthquake was felt in the Alps of southern France and along the Var River. P. M. Descotes of the Observatorio San Calixto, La Paz, Bolivia reported that an earthquake, epicenter near 15°30'S., 68°40'W., was recorded by the seismograph at $17^{h}31^{m}53^{s}$ U. T. on February 24. The computed epicentral distance was 120 km. Severe damage was caused by the shock in many villages near the epicenter and the tremor was felt strongly in La Paz.

Harold B. Foxhall, state geologist of Arkansas, reported that a light shock was felt at Fort Smith, Arkansas at $19^{h}10^{m}$ U. T. on March 4. On March 16 an earthquake was felt along the Fox River in northern Illinois. It was reported that the earthquake dislodged bottles from the shelf of a drugstore in Elgin, Illinois. The seismograph of Loyola University at Chicago recorded the disturbance at $15^{h}29^{m}$ U. T. A seismic sea wave, estimated by observers to have reached a height of 30 feet at some places, struck the east coast of North Island, New Zealand on March 25. Damage to buildings, roads, and bridges resulted from the wave. The region near the village of Gisborne was chiefly affected. The United States Coast and Geodetic Survey located the epicenter of the wave-producing earthquake in Poverty Bay off the east coast of North Island (see Table 1).

Table 1--Provisional Epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.		Epicenter				Remarks
			Lat.		Long.		
1947	h	m	°		°		
March 17	8	19.3	29	N	100	E	Sikang Province, China
March 25	20	32.2	39	S	178.5	E	Poverty Bay, off east coast of North Island. New Zealand
April 2	5	39.3	1	S	141	E	Off northern coast of New Guinea
April 14	7	15.5	45.0	N	146.5	E	Off northeast coast of Hokkaido, Japan
April 24	19	35.1	8	N	37.5	W	Atlantic Ocean, 800 miles off northeast coast of South America
May 2	2	19.0	54	N	164	W	Aleutian Islands, south of Unimak Island
May 6	20	30.7	7	S	150	E	200 miles off southern coast of New Guinea
May 8	23	52.8	61	N	139	W	Yukon, northwest Canada
May 17	7	06.7	37.5	S	180		Off North Island, New Zealand
May 27	5	59.2	2	S	141	E	Off north coast of New Guinea
June 5	22	58.2	14	N	90	W	Near coast of El Salvador
June 7	18	47.9	11	N	127	E	Near Samar, Philippine Islands
June 12	9	02.4	1	N	127	E	Near Gilolo Island
June 13	20	24.7	19	N	146	E	400 miles north of Guam
June 13	23	50.3	19	N	146	E	Aftershock

On April 1 a mild earthquake rocked homes and rattled dishes in Pompton Lakes, New Jersey. W. A. Lynch reported that the Fordham seismographs recorded an iP at $13^{h}26^{m}00^{s}$ U. T. with an S phase five seconds later indicating a distance of about 40 km.

C. F. Richter of the Seismological Laboratory, Pasadena, California supplied the following preliminary note on the southern California earthquake of April 10. The recorded times of the first motion were: Pasadena, $15^{h}58^{m}04^{s}$ U. T.; Riverside, $15^{h}58^{m}27^{s}$; Haiwee, $15^{h}58^{m}33^{s}$. A small distant shock was recorded at Pasadena at $15^{h}58^{m}07^{s}$. A portable seismometer operated at Old Woman Springs (34°25'N, 116°44'W) recorded numerous aftershocks with S-P interval of eight seconds. Aftershocks recorded at Cave Mountains (35°05′N, 116°21′W) gave S-P intervals from 3.0 to 3.5 seconds. These data indicate an epicenter about 24°57′N, 116°37′W; origin time $15^{h}58^{m}05^{s}$, not in error more than 3′ in latitude or longitude. The magnitude of the earthquake was about 6.8. The preliminary epicenter is in the Mojave Desert where field investigations are continuing. Significant damage was confined to a small area within a few miles of the epicenter. Walls were destroyed in two weak adobe structures; other buildings were cracked and dishes and bottles were broken. Cracks caused by slumping and lurching were found in the ground. The intensity barely reached IX (M-M scale 1931) in an area of Pleistocene lake deposits traversed by the Mojave River (JOHN P. BUWALDA, Pleistocene beds at Manix in the eastern Mojave Desert region, Bull. Dept. Geol., Univ. Calif., v. 7, pp. 443-464, 1914). In the vicinity of Pasadena and Los Angeles the intensity ranged from III to V.

J. E. Ramirez, reports that an earthquake, epicentral distance 170 km, was recorded at Bogotá on April 6, $22^{h}17^{m}13^{s}$ U. T. This earthquake was felt at Ibague in the Central Cordillera of Colombia.

The area surrounding Milwaukee, Wisconsin was shaken by an earthquake on May 6. The quake caused excitement but no damage was reported. A phase of a nearby earthquake was recorded at St. Louis at $21^{h}26^{m}30^{s}$ U. T.

On May 11 an earthquake was felt strongly at Twenty-Nine Palms, California. C. F. Richter of Pasadena located the epicenter at 34°15′N, 116°20′W; origin time $05^{h}06^{m}21^{s}$ U. T. The recorded magnitude at Pasadena was 4.7.

Southern Italy and the Messina region of Sicily were rocked by an earthquake on May 11. Early reports listed three killed and about 40 injured. Widespread damage was reported from about 12 towns and villages with the villages of Izca Sulonio and Santa Dello Ionio being chiefly affected. The shock was reported felt as far north as Cosenza. E. Peterchmitt reported that the P phase of this earthquake was recorded at Strasbourg at $06^{h}35^{m}10^{s}$ U. T.

The Central Observatory of Japan reported that an earthquake located about 45 miles northeast of Tokyo was felt in that city on May 20, $18^{h}55$m U. T. The shock was described as sharp.

The Instituto de Geologia, Mexico, reported that an earthquake, felt strongly in San Miguel de Allende, Guanajuato, Mexico, was recorded at Tacubaya on May 26, $18^{h}20^{m}43^{s}$ U. T. The epicentral distance was 271 km.

The earthquake of June 5, 22h58^{m} (see Table 1) was felt throughout most of Guatemala. Buildings were seriously damaged in Guazacapan near the southwestern coast.

On June 22, $23^{h}29^{m}$ U. T., an earthquake rocked the San Francisco and Monterey Bay areas of California. Windows were reported broken in Santa Cruz on Monterey Bay and dislodged boulders blocked the highway through Crittenden Pass near Watsonville. Although windows and dishes rattled and large buildings swayed no damage was reported in San Francisco.

The epicenters in Table 1 have been determined by the United States Coast and Geodetic Survey cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismograph stations.

PERSONALIA

Harold G. Bowen, Wartime Director of the Naval Research Laboratory has recently been granted an honorary degree of Doctor of Science by Brown University.

Jens Eggvin, Physical Oceanographer of the Fisheries Directorate, Bergen, Norway, and Pier Groen of the Koninldij K Nederlandsch Meteorologisch Institut de Bilt, Netherlands are in the United States, and are visiting various oceanographic and other laboratories.

Gerald FitzGerald has been appointed Chief Topographic Engineer in the U. S. Geological Survey, succeeding T. P. Pendleton who retired on April 1 following a prolonged illness.

L. R. Hafstad, Director of Research of the Laboratory of Applied Physics, Johns Hopkins University, has been granted a year's leave to fill the appointment as Executive Secretary of the Joint Research and Development Board, succeeding Lloyd V. Berkner. Ralph E. Gibson will act as the Director of the Laboratory of Applied Physics in Dr. Hafstad's absence.

John M. Hildt, Jr., until recently meteorologist with American Overseas Airlines, has accepted a position as Research Associate in the Astrophysical Observatory of the Smithsonian Institution.

Columbus O'Donnell Iselin, Director of Woods Hole Oceanographic Laboratory has been granted the honorary degree of Doctor of Science by Brown University. The citation read, "Through years of patient toil, you attained a position of leadership in a field of tremendous military and civilain significance. Through foresight and wise direction, you were able to correlate and control the vast war program of oceanographic research for the Navy. Personifying the true scientific spirit in your own labors, you added deft and tactful guidance to scholarship and learning, stimulating others to their best endeavors."

C. E. Jacob has accepted the position of Professor and Head of the new Department of Geophysics, University of Utah. Until recently, Mr. Jacob was engaged in ground water investigations with the U. S. Geological Survey.

Börge Kullenberg has been given the Heyman Prize, awarded every three years by Göteborgs Hogskola, in Sweden. This award is made every third year, alternating between literature and science. The award was made this year in recognition of Kullenberg's distinguished work in the construction of a piston core-sampler which has been used successfully as a new means for study of the ocean bed.

Robert F. Legget, until recently Professor of Civil Engineering at the University of Toronto, has been made Director of the Division of Building Research, National Research Council, Ottawa, Canada.

James A. Noble, Chief Geologist of the Homestake Mining Corporation, has been granted leave by his company in order to permit him to serve as Professor of Metalliferous Geology at the California Institute of Technology starting September 1, 1947. Dr. Noble will fill the place formerly occupied by H. J. Fraser, who is now General Manager of the Falconbridge Nickel Mining Company.

Mary Sears, Woods Hole Oceanographic Institution, received the bronze Johannes Schmitt Medal in Copenhagen in October, 1946.

H. U. Sverdrup, Director of Scripps Institution of Oceanography and Vice-President of the Union, has been given an honorary degree of Doctor of Laws by the University of California in recognition of his outstanding work in oceanography and meteorology.

Sherman A. Wengerd has recently received the degree of Doctor of Philosophy from Harvard University. The subject of his thesis is *Lithologic variation of the Viola Limestone in south central Oklahoma*. He is now engaged in exploration work for the Shell Oil Company at Wichita Falls, Texas.

F. E. Wright has retired from the staff of the Geophysical Laboratory, Carnegie Institution of Washington, but will spend some time there on a new edition of his book on "The methods of petrographic-microscopic research."

H. E. Wright, Jr. has been appointed Assistant Professor of Geology at the University of Minnesota. Until recently he was instructor of geology at Brown University.

Paul H. Boots was killed on January 22, 1947, in an airplane crash in Colombia. He was 37 years old. He was a graduate of the University of Wisconsin, and began work with the Gulf Research and Development Company in 1932 and served with them in various parts of the world. Since May 1944, he had been Assistant General Manager of the Colombian Gulf Oil Company.

V. M. Goldschmidt, Director of the Geological Museum, University of Oslo, died March 20, 1947. He was born January 27, 1888, and was considered one of the world's leading geochemists, and was the founder of modern crystal chemistry. During the War, he suffered several periods of confinement, but early in 1943, escaped to Sweden, then to the British Isles, where he worked at the MacCauley Institute for Soil Research and the Rothamstead Experimental Station.

John G. Koenigsberger, Professor at the University of Freiburg died in early December 1946. Professor Koenigsberger had been displaced by the Nazis, and suffered severely during that regime and during the War. At the end of the War he was reinstated at the University of Freiburg, but did not regain his strength after long years of privation.

George R. Mansfield, geologist of the United States Geological Survey, retired, died in Swarthmore, Pennsylvania, July 11, 1947, at the age of 71. He was born in Gloucester, Massachusetts, received his baccalaureate and master degrees from Amherst, and his doctorate degree from Harvard. During his early professional life he was an instructor in geology at Harvard and at Northwestern. He began his service with the U. S. Geological Survey in 1913, and retired in 1943.

David E. Stephens, Principal Agronomist for the United States Department of Agriculture, stationed at Pullman, Washington, died December 10, 1946. He was born at Malad City. Idaho, May 15, 1879. He received his Bachelor of Science degree from Utah State Agriculture College in 1904, and later attended the University of California. He taught at Utah State College until 1907, and then entered the service of the United States Department of Agriculture, with which he worked until his death.

K. Stephensen, Danish oceanographer, died on March 13, 1947 of pneumonia in Hellerup, Denmark.

Warren N. Thayer, Geologist with the Los Angeles County Flood Control District, died December 5, 1946 at the age of 63. He was born in Ohio and spent the early part of his professional life there on petroleum geology and hydrologic problems.

SPECIAL ANNOUNCEMENTS

(See also page 772, this issue)

International Conference on the Earth Sciences and Civilization--This conference is to be held at South Duxbury, Massachusetts, September 21-23, 1947, under the auspices of the Commission on Continental and Oceanic Structure, and the Committee on the Social Value of the Earth Sciences, International Union of Geodesy and Geophysics, Members of AGU or of IUGG who desire to attend this Conference should notify R. M. Field, Chairman of both groups (South Duxbury, Massachusetts), or J. A. Fleming, Secretary of the Commission (1530 P Street, N. W., Washington 5, D. C.) immediately.

General Assembly of International Union of Geodesy and Geophysics--A general assembly of the International Union of Geodesy and Geophysics will be held in Oslo, Norway, August 19-28, 1948. Information regarding details will be published under Special Announcements in subsequent issues of the Transactions. Persons preparing papers, or otherwise interested in the development of this meeting should write Dr. J. M. Stagg, General Secretary IUGG, Kew Observatory, Richmond, Surrey, England.

Call for copies of the February, 1947 issue--Members who no longer have need for their copies of the February, 1947 issue are requested to return them to the office of the Union at 1530 P Street, Northwest, Washington 5, D. C. Postage will be refunded.

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MINUTES OF EXECUTIVE COMMITTEE MEETING, AMERICAN GEOPHYSICAL UNION

Meeting of May 1, 1947

The meeting was called to order at 09^h15^m in the Tayloe Room of the Cosmos Club, Washington, D. C., President L. H. Adams presiding.

Present--Thirty-eight persons were present, namely: L. H. Adams; K. Hilding Beij; W. H. Bucher; Wilbur S. Burbank; Ernst Cloos; Frank L. Culley; L. P. Disney; J. A. Duerksen; R. M. Field; J. A. Fleming; R. E. Fuller; R. C. Gibbs; N. C. Grover; H. W. Hemple; M. King Hubbert; Earl Ingerson; H. F. Johnston; J. W. Joyce; David G. Knapp; Walter D. Lambert; W. C. Lowdermilk; E. C. MacKay; J. P. Marble; H. E. McComb; O. E. Meinzer; Leonard M. Murphy; Frank Neumann; Florence Robertson; Irwin Roman; Waldo E. Smith; V. C. Stechschulte; Harlan T. Stetson; W. D. Sutcliffe; H. U. Sverdrup; W. T. Thom, Sr.; R. H. Weightman; Francis G. Wells; and R. M. Wilson. J. E. Church, H. D. Harradon, H. H. Hess, L. L. Nettleton, F. W. Reichelderfer, Edward H. Smith, L. G. Straub, and Thomas G. Thompson were excused because of previous engagements.

Approval of minutes--The minutes of the meetings of October 25, 1946 and November 29, 1946, were published in the December, 1946, and February, 1947 issues of the Transactions, respectively [v. 27, no. 6, pp. 903-915, and v. 28, no. 1, pp. 145-147]. No corrections were received, and the minutes were approved as published.

General Secretary's Report

Personnel--Miss Marion Geoffroy resigned as Electromatic Operator and Editorial Assistant, effective February 15, 1947 to continue academic work, and Miss Margaret Lathrop was engaged beginning January 23, 1947, in her place. Miss Olive Phillips was employed as Secretary effective February 1, 1947. With the removal to the new location at 1530 P Street, Northwest, late in January, the part-time services of the personnel of the Department of Terrestrial Magnetism were no longer available and it was essential to engage a regular full-time secretary for this work in accordance with funds provided in the budget.

Financial Report--The financial report for the fiscal year ending June 30, 1947, will be prepared promptly at the close of the year, for submission to the Committee on Audit.

The cash balance on April 1, 1947, in all funds of the Union, was $18,940.24, which included $14,474.03 for the Union, $153.10 for the William Bowie Medal fund, and $4,313.11 for the special fund left to the Union by the late Robert E. Horton. In accordance with the instructions of the Executive Committee, October 25, 1946, five $500 Series F Government bonds were purchased at a cost of $1850. These are not included in the above total.

It was approved that $500 and $200, respectively, of unexpended budgeted funds in other items might be transferred to the items for Transactions, and for stationery and miscellaneous.

Membership--The membership as of April 27, 1947 was 2966, including the third list of 1947, on which balloting is under way. In addition there are over 60 applications ready for action as the fourth list will bring our total membership well over 3000 by the end of May. A capitulation of the membership since October 23, 1946, gives the following:

Members, October 23, 1946		2843	
Inactive to active status		6	
New members, 1946	73		
New members, 1947	128	201	
New Corresponding member		1	3051
Active to inactive		2	
Resignations		67	
Deceased		11	
Dropped		1	81
			2970
Adjustment since October 1943			-4
Membership, April 27, 1947			2966

The eleven deaths recorded since October 23, 1946 are: Henry G. Avers, January 19, 1947; H. H. Clayton, October 27, 1946; Oskar T. Dauelsberg, September 15, 1946; Alfred C. Gregory, November 30, 1946; Gleason W. Kenrick, October 29, 1946; G. F. Loughlin, October 22, 1946; Wm. A. Mattice, October 29, 1946; A. E. Staniland, June 28, 1946; F. W. Stiefel, July, 1946; David E. Stephens, December 14, 1946; and Warren N. Thayer, December 5, 1946.

The dropping of names of 32 members in arreas in dues for 1945 and 1946, was approved with the exception that the office of the Union was instructed to made one final attempt to bring these members into good standing, and with the further exception that those who are, or have been in the armed services, may be later reinstated, either on payment of back dues (in which case back Transactions not previously sent insofar as available, would be sent), or to the beginning of a calendar year by the payment of dues then current.

Administration of the Union--In January, 1947 the offer was made to the Union of space in the Administration Building of the Carnegie Institution of Washington at 1530 P Street, Northwest. The central location and the excellent quarters offered are decidedly to the Union's advantage, and the office was moved late in January, 1947 from 5241 Broad Branch Road, Northwest, where the Union activities had long been centered, to the new address.

Organization of the Tennessee Valley Branch--In 1945 the Executive Committee granted authority for the organization of the Tennessee Valley Branch providing the suggested provisions for such Branches in the Statutes and By-Laws were acted upon favorably. Following favorable action the Tennessee Valley Group was advised, but unsettled conditions caused delay in organization. On March 21 an organizational meeting was held which President Adams attended as guest speaker. Since that time the Group has transmitted its proposed Statutes and By-Laws for approval by the Executive Committee. The Committee on Statutes and By-Laws covered this matter in their report [see Appendix 1].

National Research Council--The Council has made a grant of $400 to the Union for the fiscal year ending June 30, 1948. The National Research Council is now making a survey relating to patent policies by educational institutions and non-profit research organizations. Any members who have had experience along this line or given thought to this matter should get in touch with Archie M. Palmer, Director of the Survey at the National Research Council.

Publications--Since October 25, 1946, the Transactions of October and December 1946, and February and April for 1947, have been published and distributed to the members in good standing, to subscribers, to those with whom exchange arrangements have been made, and without charge to organizations and colleagues abroad.

International Union of Geodesy and Geophysics--Plans are proceeding for the General Assembly of the International Union to be held in Norway in September, 1948. There is a balance in the American funds of the IUGG of $25,149.23. The United States has paid dues in full for the war years.

Meetings--The Southwestern Pacific Regional Committee of the Section of Hydrology held the Nineteenth Regional Meeting of the Union at Pasadena, California on February 15, 1947; about 100 members and guests were in attendance. F. J. Veihmeyer is Chairman of the Regional Committee and Franklin Thomas of Pasadena was in charge of local arrangements. The Twentieth Regional Meeting was held in the North Pacific Region by the Committee of the Section of Hydrology in Portland, Oregon, April 21-23, 1947, in cooperation with the Western Snow Conference and the Columbia Basin Water Forecast Committee; no report has yet been received of this Meeting. J. C. Stevens is Chairman of the Regional Committee and George G. West its Secretary, who acted in charge of local arrangements.

On the basis of the enthusiastic endorsement of the idea for a regional meeting to be held in the New England area the officers of the Union appointed a General Committee for this Meeting consisting of the following: Richard M. Field, Chairman; C. F. Brooks; C. O'D. Iselin; H. B. Kinnison; J. W. Peoples; and H. T. Stetson. Plans are well under way to hold the meeting during September 16-21, 1947. The Twenty-Eighth Annual Meeting of the Union has just been held with a total registration of 764.

National Roster--Word from the National Roster indicated that their vocational booklet entitled, "Geophysics as a Profession" should be received from the printer very soon. (This 24-page leaflet is now available through the National Roster, Labor Department, Washington 25, D. C., the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D.C., or the office of AGU.)

Inter-Society Committee on Science-Foundation Legislation--In January the American Geophysical Union was requested to designate representatives to act on the Inter-Society Committee on Science-Foundation Legislation, which was then being organized by the American Association for the Advancement of Science. Pending definite action on this by the Executive Committee, President Adams designated that the Vice-President and General Secretary of the Union act as representatives. It is approved that the policy suggested by the President be adopted by the Union with regard to the representatives, with the understanding that these representatives shall not decide matters of policy on behalf of the Union. The status of the activity of this Committee is reported currently in Science.

UNESCO--The International Council of Scientific Unions and UNESCO have concluded an agreement defining the interrelationships. On the invitation of the State Department President Adams named John Putnam Marble and W. F. G. Swann as representatives to a National Conference on UNESCO held in Philadelphia, March 24-26, 1947. Their report is herewith [see Appendix 2]. Another meeting is being held in Denver, May 15-17, 1947, and the President has designated C. A. Heiland, A. H. Koschmann, and H. S. Riesbol as representatives for the Union. It was agreed that it is important that representatives of the Union attend these meetings whenever and wherever possible in order that we may be fully informed.

Cooperation of the American Standards Association Committee Z-38 on Photography--Commander C. G. Mattison, who has acted as our representative on this Committee has resigned because of official assignment elsewhere. A new representative will be appointed soon.

Letters to officers, present and past, requesting suggestions regarding finances--Several excellent suggestions came to the office of the Union in response to President Adams' letter of January 15, regarding the subject of finances of the Union. Application has been made to the Rockefeller Foundation for an additional grant of $7500 for the coming triennium. (Note: This has subsequently been refused because the Rockefeller Foundation is specifically directed by the Board of Trustees to give aid principally in fields other than the physical sciences.) An active compaign has been undertaken to secure new individual members and plans are well under way to canvass the field for corporation members.

Committees--G. W. Musgrave, who acted very effectively as the Chairman of the Membership Committee during 1946, found, as the year drew to a close that official duties, with much time out of the city, prevented him from carrying on the functions of the Chairman of this Committee as effectively as he desired. He asked to be relieved of those duties temporarily, and Irwin Roman was appointed Acting Chairman. In February Musgrave found that the continued pressure of his official duties prevented his performing the duties of an active Chairman, and resigned. I. Roman has carried on actively in the interim and will continue to the end of the present administration. He is being well supported by his Committee, but especially H. Freeborn Johnston is to be commended for his active work in securing over a hundred new applicants during the spring.

Washington Group, Section of Hydrology--The Fifth Meeting of the Washington Group of the Section of Hydrology was held on April 3, 1947. Ralph R. Will addressed the Group on the subject, "Present and future outlook of governmental participation in natural resource development work." New officers were elected as follows: Chairman, Carl F. Izzard; Vice-Chairman, Howard Williams; and Secretary, Bernard Frank.

Elections--The reports in the Section Meetings and in the General Assembly concerning the elections precludes necessity of a further report here [Trans., v. 28, pp. 496 and 497].

Miscellaneous--Science Service has offered to send privilege cards to our members, offering a $1.50 discount on the regular subscription rate to the weekly Science News Letter. Considering that Science Service is a non-profit organization serving the general field of Sciences, the plan was approved.

Action on General Secretary's Report--Matters requiring action were acted upon as reported above, and the report was accepted.

Reports of Standing Committees

Membership--Chairman Roman reported with regard to the plan to circulate the membership, inviting members to send in names of prospective members. He also outlined the plans for inviting organizations to become Corporation Members.

He reported that Pentti Eskola of Finland was nominated for Corresponding Membership, because of his outstanding work in Tectonophysics, by several members of the Union, and that the Membership Committee, by mail ballot, had unanimously voted to recommend him favorably to the Executive Committee. The Executive Committee accepted the recommendation, and Professor Eskola was declared elected a Corresponding Member.

Budget--Chairman Wilson presented the budget recommended by the Committee for the fiscal year ending June 30 1948 [see Appendix 3]. He pointed out that in the Committee's report of a year ago [Trans., v. 27, p. 612] the Committee had shown the urgent necessity of increasing the Union's income, in order that there may be a more equitable balance between receipts and expenditures. He mentioned that the Rockefeller Foundation grant ($20,000 for the triennium) terminated with the current fiscal year, and that the amount ($7000) secured through that grant during the current fiscal year would need to be supplied by some other source of income to avoid an excess of expenditures over receipts. He suggested that one way of accomplishing this would be through an increase in dues, and suggested that a letter be sent to the membership concerning the situation and this recommendation. Fuller suggested the establishment of a contributing membership. Hubbert supported the idea of an increase in dues.

Chairman Wilson recommended that the suggestions as to the means of meeting the budget in future years be transferred to New Business, and that the Committee act first with regard to the approval of the budget submitted. The General Secretary then spoke with regard to the Union's experience in financial matters, and pointed out that the past history of the Union afforded ample evidence that with normal growth and development, financial needs would be met. The Union's work requires full faith for the future. A motion to approve the budget for year ending June 30, 1947, was approved, with the understanding that this carries with it, the approval of the salary of the Executive Secretary.

A motion was unanimously adopted complimenting the Executive Secretary upon his splendid service to the Union.

Statutes and By-Laws--Chairman Harradon, who was unable to be present, communicated the recommendations of the Committee regarding the Statutes of the Tennessee Valley Regional Branch of the Union. These together with the By-Laws are published in Appendix 1. The recommendations and the Statutes were approved.

Reports of Special Committees

Award of the William Bowie Medal--Chairman Bucher reported regarding the unanimous selection by the Committee of F. A. Vening Meinesz to be the Ninth Recipient of the William Bowie Medal. This was unanimously accepted.

New Business

With regard to the recommendation of the Committee on Budget that a Ways and Means Committee be established, it was agreed that action on this be deferred until the next meeting of the Executive Committee, and to instruct the new Committee on Budget that it should act in this broad capacity. Lambert suggested that this Committee should be a strong one, and with the Committee on Membership and the Committee on Statutes and By-Laws, act as a policy-making council. No action was taken on this suggestion.

The matter of regional meetings was discussed and the feeling prevailed that we should attempt to have more of them, and, where there is local interest in such meetings, the Union as a whole should give support. On the Pacific Coast, there has been considerable interest in a general regional meeting. The Section of Hydrology has had a number of meetings, both in California and in the Northwest, and the thought prevailed that this might well be extended to include the broad field of Geophysics. Sverdrup was requested to act informally in regard to such a meeting, enlisting the cooperation of Veihmeyer, Stevens, and others who have been active in the arranging of regional meetings in Hydrology, as well as those in other fields, and who can aid in making such a meeting a success.

There was also a general discussion of symposia, with the thought generally supported that these should be developed for regional and annual meetings, whenever a suitable topic is presented. Such symposia should, where possible, develop the interrelationships of the various branches of Geophysics.

Marble commented that at the present time there is no national organization of the geochemists, and believed that they should be invited to membership and that the activities of the Sections of Volcanology and Tectonophysics, especially, be broadened to make such membership more attractive to this group. A symposium including the geochemists was suggested. This met with general approval, but no formal action was taken.

The meeting adjourned at 12^h03^m

Jno. A. Fleming, General Secretary
Waldo E. Smith, Executive Secretary

APPENDIX 1--REPORT OF THE COMMITTEE ON STATUTES AND BY-LAWS

The Statutes of the Tennessee Valley Regional Branch of the Union were submitted to the Committee on Statutes and By-Laws on the evening of April 23, 1947. Each member of the Committee has carefully examined these Statutes to determine whether they are in comformity with the Statutes and By-Laws of the Union. As no passage was found to which objection in this respect could be raised, the Committee recommends approval of the Statutes in question. These Statutes are as follows:

Tennessee Valley Regional Branch

Preamble

The Tennessee Valley Regional Branch of the American Geophysical Union is hereby established in accordance with Article 10 of the Statutes and the ninth By-Law of the American Geophysical Union.

Statutes

Article 1: Name, Location, and Objective

(a) This organization shall be the Tennessee Valley Regional Branch of the American Geophysical Union.

(b) The location shall be the region within the drainage basin of the Tennessee River.

(c) The objective of this organization shall be to promote the aims and objectives of the national organization within the geographical area covered by the branch.

Article 2: Membership

(a) Members of this organization shall be members, in any grade, of the American Geophysical Union who reside within the geographical region stated in Article 1 (b).

(b) A Member shall be any eligible person who has paid his dues for the fiscal year July 1 to June 30.

Article 3: Dues--The members shall pay annual dues of $1.00.

Article 4: Officers

(a) The officers of this branch shall consist of three Directors, a President, a Vice-President, and a Secretary-Treasurer.

(b) The term of office for the Directors shall be for three years with one member elected each year. A Director may be elected for two or more consecutive terms.

(c) The term of office for the President and Vice-President shall be for one year.

(d) The Secretary-Treasurer shall be appointed by the Board of Directors and shall hold office until relieved by the Board of Directors.

(e) A vacancy in any office shall be filled for the unexpired term by the Board of Directors.

Article 5: Board of Directors--The Board of Directors shall be the governing body and shall consist of the three Directors and the President. The President shall be Chirman of the Board.

Article 6: Nomination and Election of Officers.

(a) Nomination--The President shall appoint a Nomination Committee who shall submit to the Secretary at least one month before the annual meeting a list of nominees. Additional nominations may be made by written petition of five or more members.

(b) Election--The officers shall be elected by mail ballot. The ballots shall be mailed to the membership at least three weeks before the annual meeting and shall be in the hands of the Secretary one week before the annual meeting.

Article 7: Meetings

(a) The annual meeting shall be held during the month of April at a time and place to be designated by the Board of Directors.

(b) Monthly meetings shall be held except during the months of July and August.

Article 8: By-Laws--By-Laws governing the order of business may be enacted by an affirmative vote of two-thirds of the members present at any regional branch meeting provided at least one-third of the members are present at the meeting.

Article 9: Amendments--The Statutes may be amended by an affirmative vote of not less than three-quarters of the members. The proposed amendment shall be brought up for discussion at the annual meeting. The Secretary shall mail ballots to all members immediately after the annual meeting and shall count the ballots 30 days after the annual meeting. Any amendment which is ratified shall be effective as of the date of the annual meeting at which it was discussed.

Article 10: Sub-Regional Branches--Sub-regional branches may be formed upon approval of the Board of Directors.

APPENDIX 2--REPORT OF DELEGATES FROM THE AMERICAN GEOPHYSICAL UNION TO THE NATIONAL CONFERENCE ON UNESCO, PHILADELPHIA, PA., MARCH 24-26, 1947

Acting on the basis of written requests from President L. H. Adams of the Union, W. F. G. Swann and J. P. Marble attended the National Conference on the United Nations Educational Scientific and Cultural Organization held in Philadelphia, Pennsylvania from March 24 through March 26, 1947. The general sessions of the conference were attended by both delegates, and one was able to attend two of the Section Meetings: those on "The Natural Sciences in UNESCO" and on "The International Exchange of Persons." The following remarks appear to be worth while calling to the general attention of the membership of the Union.

This conference was of a preliminary nature. The organization of UNESCO on a national basis is just beginning, and it was necessary to spend a great deal of time explaining to a large body of persons of different backgrounds, skills, and special interests what the organization hoped and planned to accomplish, and what had been accomplished by the previous international meetings. The chief accomplishments of the present conference were in the section meetings where were explored the ways in which existing organizations in all the various fields could assist UNESCO in improving international cooperation and understanding, and the ways in which UNESCO could assist existing organizations and groups on an international scale. There was also discussion, usually of a very clearing nature, as to the fields where UNESCO could cooperate with existing agencies, and those where no agencies, or inadequate agencies were in existence.

It appears that, in the field of international cooperation in the natural sciences which is of particular interest to the American Geophysical Union, UNESCO is well informed as to the condition of the existing agencies, be they councils, unions, congresses, or others; that UNESCO will not interfere with the working of existing groups that are now functioning in an effective manner; that UNESCO will utilize existing channels of international cooperation in science as far as such channels exist, and will endeavour to improve them if need be; that UNESCO will try to prevent the establishing of competing agencies or organizations in the same or similar fields. The Secretariat of UNESCO appears to be impressed with the much better condition of international cooperation in the natural sciences than in any other field, and plans to use this as a model for others. It plans to give all possible aid to the International Council of Scientific Unions and its constitutent unions, and will not try to supersede them or it.

UNESCO hopes to be able to assist in the diplomatic, financial, and using fields in the international exchange of persons, in particular as regards visiting scholars, exchange students, and visiting or loaned official scientific government experts. The general field of exchange of persons at present appears to have too many organizations and other bodies in it, many of which are of a rather vague character, and there is very little known by one group about any of the other groups.

The general sessions, three in number, were devoted in the main to addresses of the inspirational type, which were of great value in this instance, as many of the delegates had only vague notions of what the whole thing was about, and needed information and ideas as to how to describe and "sell" UNESCO when they get back home.

The chief lack of the present organization appears to be, in the view of many of the delegates, that the USSR is not represented. It appears that no action of any kind has as yet been taken by that country as regards UNESCO, so it is too early to say whether world-wide cooperation will be possible or not. In the meantime, UNESCO will serve an extremely valuable purpose, provided it keeps its feet on the ground and utilizes existing efficient organizations as fully as possible.

It appears that the American Geophysical Union should keep itself informed as to the work of UNESCO in the fields of interest to the Union, and should use its services when the need arises. It also appears that the work and field of the Union are presumably known to UNESCO through the International Council of Scientific Unions by way of the International Union of Geodesy and Geophysics,

It is suggested that the officers of the Union consult with the officers of the National Research Council to define and delimit the roles of the two parties in this connection, since the National Research Council had its own representatives at the conference.

See Appendix 3(Budget) on next page

APPENDIX 3--BUDGET FOR FISCAL YEAR ENDING JUNE 30, 1948

W. M. Wilson, Chairman
R. W. Goranson H. N. Eaton

The following budget for fiscal year 1947-1948 was approved by the Executive Committee.

Assets:		
Balance in bank, June 30, 1947, estimated		
Regular Union funds	$12,000.00	
Special, Horton Fund	4,000.00[a]	
U. S. Government Bonds (at cost)	1,850.00	
Bills receivable, including some of the dues in arrears[b]	2,400.00	$20,250.00
Grants:		
National Research Council		400.00
Anticipated Income:		
Dues 3000 (net[c]) members for 1948	$15,000.00	
Sales, *Transactions* and reprints	4,000.00	$19,000.00
Total estimated receipts and assets		$39,650.00
Suggested Expenditures:		
Transactions, three numbers, v. 28, and three numbers v. 29 (900± pages), including services of I. B. M. operator	$ 7,200.00	
Reprints	2,000.00	
List of members and officers	750.00	
Bibliography of Hydrology, 1941-1947 (if manuscript is prepared by Section of Hydrology)	700.00	
Services, Executive Secretary	6,000.00	
Stenographic and clerical services	5,400.00	
Expenses, 29th Annual Meeting	500.00	
Expenses, Regional Meetings	250.00	
Expenses of Sections	100.00	
Expenses of Committees	500.00	
Honoraria to co-editors	1,500.00	
Postage and communications	1,000.00	
Stationery and miscellaneous	1,000.00	
Bowie Medal	20.00	
Travel	300.00	
Expenditures of R. E. Horton Fund[a]	4,000.00	
Office equipment	600.00	
Bills payable other than those estimated in arriving at balance in bank June 30, 1947	130.00	
Total suggested expenditures		$31,950.00
Estimated balance June 30, 1948		$ 7,700.00[d]

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[a] This includes a balance of $4,000 (estimated) remaining from the fund left to the Union by the late Robert E. Horton for the purpose of completing some of his unfinished manuscripts and, therefore, not available for general expenditures.

[b] This item assumes that a certain part of unpaid dues will not be paid because of resignations, and dropping of any becoming two years in arrears.

[c] Past records of the rate of increase in membership indicate that our rolls will well exceed 3000 in 1947, but the estimate of income from dues is made conservatively on 3000 members, the approximate membership in late April 1947.

[d] It is to be noted that this balance must apply against expenditures during July to December, 1948; that is, before dues of 1949 become available.

Transactions, American Geophysical Union Volume 28, Number 4 August 1947

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, MAY 11 TO JULY 10, 1947

Addington, Prof. Arch R., Fresno State College, Fresno 4, Calif. (bg)
Allen, Mr. Arthur E., 708 Centennial Ave., Sewickley, Pa. (g)
Arelleno, Sr. A. R. V., Apartado 7525, Mexico, D. F. Mexico (fgh)
Aston, Mr. Charles A., Jr., 302 Booker Bldg., Artesia, N. Mex. (abd)
Austin, Mr. Thomas S., Divison of Oceanography, Hydrographic Office, USN, Washington 25, D. C. (e)
Baker, Mr. Charles L., State Geological Survey, Vermillion, S. Dak. (a)
Banerjee, Dr. Santi Lal, 1412 John Jay Hall, Columbia University, New York 27, N. Y. (bd)
Barnes, Mr. James V., Dept. of Geology, Indiana University, Bloomington, Ind. (fg)
Bartle, Prof. Glenn G., Triple Cities College, Syracuse University, Endicott, N. Y. (bdh)
Baum, Mr. Werner A., Dept. of Meteorology, University of Chicago, Chicago 37, Ill. (ceg)
Baxter, Mr. George W., 19 Roylesden Crescent, New Oscott, Sutton Coldfield, Warwicks, England (abcdefgh)
Beach, Mr. John H., 531 California Ave., Bakersfield, Calif. (abce)
Beal, Mr. Carlton, 5658 Wilshire Blvd., Los Angeles 36, Calif. (b)
Beck, Mr. August F., Tropical Oil Co., Rogota, Colombia (b)
Benson, Mr. William E., U. S. Geological Survey, Washington 25, D. C. (ceg)
Berg, Dr. John R., University of Wichita, Wichita, Kans. (fh)
Blanpied, Mr. Bernerd W., P. O. Drawer 1731, Shreveport 93, La. (befh)
Bloomer, Dr. Phillip A., Jr., 934 Unadilla St., Shreveport, La. (bh)
Brown, Mr. Maurice E., Illinois Division of Waterways, 201 W. Monroe, Springfield, Ill. (beg)
Bumpus, Mr. Dean F., Woods Hôle Oceanographic Institution, Woods Hole, Mass. (e)
Burlew, Dr. John S., 2801 Upton St., N. W., Washington 8, D. C. (fh)
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Callan, Prof. John A. C., 3819 Military Road, N. W., Washington 15, D. C. (g)
Carey, Prof. S. Warren, University of Tasmania, Hobart, Tasmania (abcdefgh)
Cathcart, Mr. James B., Jr., P. O. Box 829, Carlsbad, N. Mex. (ef)
Clark, Mr. Stuart K., Continental Oil Co. Ponca City, Okla. (gh)
Cobban, Mr. William A., Dept. of Geology, Johns Hopkins University, Baltimore 18, Md. (e)
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Duncan, Mr. Donald C., U. S. Geological Survey, Washington 25, D. C. (f)
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Farrow, Mr. Verle, Route 2, Falls Church, Va. (g)
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Freeman, Dr. Louise B., 608 Elsmere Park, Lexington 16, Ky. (e)

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Fryxell, Dr. F. M., Augustana College, Rock Island, Ill. (g)
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Groen, Dr. Pier, Kon. Ned. Met. Inst., DeBilt (U), Netherlands, (ce)
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SPECIAL ANNOUCEMENTS

(See also page 660, this issue)

New England Meeting of the American Geophysical Union--The Twenty-First Regional Meeting of AGU will be held as a general meeting of the Union from September 17-20, 1947 as follows:

September 17, Wesleyan University, Middletown, Conn.; Conference on the Major Problems in the Tectonophysics of the New England Area; Chairman, Professor Joe Webb Peoples (Department of Geology, Wesleyan University).

September 18, Woods Hole Oceanographic Institution, Woods Hole, Mass.; Conference on Earth Sciences from the Oceanographic Point of View; Chairman, Director Columbus O'D. Iselin (Woods Hole Oceanographic Institution).

September 18-20, Institute of Geographic Exploration, Harvard University, Cambridge, Massachusetts; Conference on Meteorology, Hydrology, and Cosmic Phenomena; Co-Chairmen, C. F. Brooks (Director, Blue Hill Observatory, Milton, Massachusetts), Harlan T. Stetson (Director, Cosmic Terrestrial Research Laboratory, Needham, Massachusetts), H. G. Houghton (Head, Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Massachusetts), and H. B. Kinnison (District Engineer, U. S. Geological Survey, Boston, Massachusetts). On the afternoon of September 18, a trip will be made to the Blue Hill Observatory and to the Cosmic Terrestrial Research Laboratory. The other portions of this interval will be devoted to scientific sessions with those in Hydrology extending into the morning of September 20.

It is suggested that those desiring further details write directly to conference chairmen or to Richard M. Field, General Chairman of the New England Meeting, at South Duxbury, Massachusetts.

TRANSACTIONS
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SOME UNSOLVED PROBLEMS OF GEOPHYSICS

Leason H. Adams

(Address as Retiring President of the American Geophysical Union)

Abstract--After a brief review of what is already known about the whole Earth, from the upper limit of the atmosphere at several hundred miles above the surface down to the very center at a depth of four thousand miles, attention is called to six of the particularly baffling problems in geophysics. These are: The origin of mountain chains; the origin of geosynclines, that is to say, the great troughs or depressions that existed during geologic times at various places on the Earth, that by filling with the products of erosion washed down from adjacent land areas are intimately associated with the great deposits of limestone, shale, and sandstone, often amounting to several miles in thickness; the cause of igneous activity, including volcanism, a group of phenomena that continue to give us striking evidence of a hot and active interior of the Earth; the origin of deep-focus earthquakes, that is, the ones caused by some still mysterious processes at depths of as much as four hundred miles below the surface; the origin of the Earth's magnetic field about which much is known, but of which the underlying cause is still uncertain; and the temperatures prevailing in the interior of the Earth, a knowledge of which would provide a clue for solving many other problems. It is urged that more effort be devoted to scientific investigations in the several branches of the physics of the Earth, utilizing all possible theoretical as well as experimental methods.

Introductory

Ever since Pythagoras announced his great discovery that the Earth has a spherical form, man has speculated from time to time on the nature of the Earth as a whole; but in the succeeding more than two thousand years our knowledge of the globe on which we live remained superficial--in the literal as well as in the figurative sense of the word. In recent decades the accelerated advance of science on all fronts has brought us an imposing array of facts and principles concerning the Earth; and, even though sometimes fact has been confused with fancy, and theory mistaken for theorem, we have much fascinating new knowledge about the structure, composition, and physical properties of the Earth down to its very center and up to the limit of its atmosphere.

Scope of geophysics--My subject for this presentation is some unsolved problems of geophysics. Before discussing some of the puzzles that still challenge the ingenuity of those who devote their attention to the Earth sciences, I should like to pause for a moment to make a remark or two about the word geophysics, and then to list a few of the types of information that have already been acquired and to mention briefly some of the more important principles that have been established.

Geophysics is derived from two Greek roots, referring respectively to the Earth and to Nature. It is interesting to observe that geophysics, as a word used to describe a branch of science, is of recent origin, as may be seen, for example, by noting that the thorough and comprehensive Eleventh Edition of the Encyclopedia Brittanica, published in 1910, contains no such entry. Today, the word has become so popularized and has been used in so wide a variety of senses that it threatens to degenerate into a meaningless term. Now, discussions of terminology are likely to be very dull, but I feel I should specify the scope of the general subject to which I am directing your attention. Geophysics means simply the physics of the Earth. With that simple starting point, no one should have any difficulty in agreeing upon answers to such queries as, "How much territory should the science that is given this name be deemed to cover?" "Does geology include geophysics, or vice versa?", "Where does geophysics leave off and geochemistry begin?" The last question has been a favorite subject of debate since scientists began to be geo-minded. In this connection, it is interesting to recall that shortly after the American Geophysical Union was established a number of its members professed to be disturbed by the circumstance that a great part of the activities of the Geophysical Laboratory of the Carnegie Institution of Washington, which had specialized in that part of geophysics dealing with the melting of rocks and their formation from molten magmas, had found no proper niche among the seven existing branches of the Union, and that as a result an eighth section--later abolished--called geochemistry was set up. The labels geochemistry and geophysics, the proper use of which is a subject for continuous debate, will, of course, never be applied unambiguously so long as chemistry and physics themselves remain as overlapping sciences. The domain of physics, from its general name, is natural phenomena, and that of chemistry may be described as the molecule and its component atoms. At one time, it may have been practicable for physics to confine its attention to matter in bulk, and for chemistry to deal primarily with the atom, giving consideration only incidentally to physical properties of materials. But in recognition of the artificiality of this distinction, the name physical chemistry was added to hide what may have appeared to be the unwarranted infringement of one domain upon another. This device did not settle the matter, and indeed it seems profitless to attempt to do so. I cannot readily visualize a working agreement whereby, for example, physics would be understood to deal on the one hand with the properties of matter in bulk and on the other the behavior of the nuclei of atoms, while chemistry would be understood to occupy the middle ground and to deal primarily with phenomena dependent upon the outer, or valence, electrons. If I were to express a preference--which in view of my early training as a chemist could not fairly be called prejudiced--it would be based upon the greater generality of the word physics, which logically might well be used for the sum total of natural phenomena. Likewise, and even more logically, geophysics could cover all scientific work dealing with the formation and properties of the Earth and its several parts. Geology is the older and better known field of Earth science. Originally an observational and interpretive science, it has become more and more dependent on physics and chemistry. Fortunately for your speaker, it is not vital to decide at this time where geology leaves off and geophysics begins. In presenting this matter about geophysics to you, I am using the term in its broadest sense, and I am carefully avoiding the necessity of having to determine whether an investigator who is interested in volcanism and is applying modern techniques to the study of the composition of volcanic products is a geophysicist on Mondays, Wednesdays, and Fridays and a geochemist on the remaining days of the week, or whether his work should be more properly described as experimental geology.

Some problems that have been solved

Turning now to my main subject, I should like to say a few words first concerning the knowledge that has already been gained as to the Earth and Earth processes. Most discussions on subjects as broad as geophysics go into too much detail. I shall deliberately try to be too general. The intensive investigations of the past few decades have afforded us a rich store of facts and conclusions. Indeed, so much has already been learned that at this time I can hardly more than make the assertion and fortify it with a few illustrations. In addressing a group composed largely of members of the American Geophysical Union, I should perhaps take cognizance of the circumstance that the Union is made up of eight sections, namely, Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, Hydrology, and Tectonophysics; and, whereas all of these subjects are inherently of great importance, it might be expected that I should impartially apportion my remarks among the eight subjects. I cannot promise to be so systematic; the personal element enters here and I must perforce choose my examples, both the solved and the unsolved problems, somewhat by whim or accidental interest.

Beginning at the outermost limit of the atmosphere and working downward, let us then note some of the facts that have been established concerning the Earth. Of great interest and vast practical importance are the properties of the ionosphere, which may be defined as a series of ionized layers extending from a heighth of somewhat more than two hundred miles down to about fifty. Three principal layers are now recognized, namely, E, F1, and F2 layers, the heighths of which vary both regularly and irregularly with season, time of day, and other factors. The measurement and description of the ionosphere are noted for the use of ingenious and elaborate experimental techniques.

The lower regions of the atmosphere form the special province of meteorology for which investigators have made remarkable progress in the observation and interpretation of the complicated motions of the atmosphere and in solving complex problems of fluid dynamics. Hardly any subject has a greater impact on human activity than the weather. Quite apart from its value as a stimulus to flagging conversation, the weather constantly influences our daily lives and regulates a considerable part of the world's activities.

Coming closer to the solid Earth, we look in the direction of the oceans, which taken together cover three-quarters of the surface of the globe with a layer of water averaging three kilometers in thickness. The oceans, long a source of mystery, have been patiently investigated, and the variety of puzzling problems relating to movement and to the properties down to great depths have been given a satisfying answer.

Running water has also been the subject to which careful attention has been given. Studies of stream flow and ground water have tied in closely with other branches of Earch sciences and the observations and generalizations have illuminated puzzling problems in other fields.

Arriving now on dry land, we note that the Earth is surrounded by a layer called the "crust." This varies in thickness from place to place, averaging about thirty miles, and consists of a complex series of rock formations commonly twisted, folded, and distorted in other ways. No longer is this outer layer supposed to be a true crust floating on an underlying liquid mass. Its distinctive feature is that it differs in composition and homogeneity from the solid material that lies beneath. The form assumed by the Earth's surface is known with remarkable precision through the efforts of the geodesists, who also by elaborate measurements of the force of gravity have firmly established the existence of isostatic adjustment within and just beneath the crust, just as if despite the high "solidity" of the Earth the deeper material yields sufficiently by plastic flow to permit heavy masses to sink down forming low-lying areas, and light masses to float high forming uplifted regions, including mountain ranges. Geological investigations have given us a great mass of information on the forms, inter-relations, and past history of rock formations. We have come to believe that throughout the crustal layer the two most common types of rock are just those igneous rocks that the geologist finds most abundantly at the surface, namely, granitic and basaltic. The careful interpretation of seismological records using refined mathematical techniques has gone far towards giving us a picture of crustal structure. Furthermore, from measurements of temperatures in bore holes, which temperatures always increase steadily downwards, we infer also that the interior of the Earth is very hot, and by measurement of the small but significant quantities of radioactive elements in crustal rocks, we have been able to reconcile existing temperature gradients with that great age of the Earth--two or three thousand million years--demanded on geological and biological grounds, and indicated more precisely by experiments with radioactive materials.

It is now generally believed that beneath the crust and half way down to the center of the Earth we have a relatively simple rock of the nature of a peridotite. Here again seismology has afforded us far-reaching conclusions. The mystery of the far interior of the Earth has begun to be cleared up, but each question that is answered has led to other intriguing problems to be solved.

Finally, in our rapid inspection of the whole Earth from the geophysical point of view, we come to the central region which is occupied by an iron core roughly half the diameter of the Earth. The existence of the iron core, which, incidentally, is a conclusion that is perhaps more definite than any of the other inferences concerning the interior, is not only interesting itself but has a bearing on fundamental questions relating to the origin of planets.

What I have just said is not to be considered a summary of existing knowledge concerning the Earth, or even a complete listing of the major subjects, but rather it is merely a small sample of the types of information that we now possess. All of the great discoveries in geophysics previously made give us encouragement to attempt solution of the unsolved problems, some of which will now be discussed.

Six broad problems awaiting solution

Origin of mountain chains--Geologists classify mountains in several categories such as, for example, volcanic mountains, plateau remnants, domal mountains, and folded mountains. The wealth of detailed description concerning all types of mountains sometimes tends to obscure the striking nature of the great mountain chains like the Rockies, the Alps, and the nearby Appalachians. One stage in the complex history of a mountain chain is the compression of the rock formations in a horizontal direction, as if by tremendous lateral forces, producing folding, fractures, and overthrusting, and related crustal movement of almost infinite variety. There is also a general uplift as if by forces exerted vertically, which may not be contemporaneous with the folding. What produces the compression? Is the broad uplift caused by the same factors? What special circumstances caused mountain building to be confined to certain regions of the surface? Why is the orogenic activity in such regions repeated several times?

Many attempts to answer these questions have engaged the attention of the best minds, but the existing answers leave much to be desired. Complicated mechanisms in great variety have been adduced, but in all instances cogent objections have been raised. Prominent among the attempted explanations is the thermal contraction theory, which has been developed in detail by numerous investigators. According to this theory, the differential contraction in the successively deeper layers of the Earth produces the tendency for the outer layers to compress and thus produce warping and folding. As the Earth cools, the temperature gradient of the outer few hundred miles of the Earth becomes less steep. This statement is equivalent to saying that the material at moderate depths cools more, and hence shrinks more, than the material either above or below. The body of the Earth would thus tend to shrink away from the skin, which then being too large to fit snugly would wrinkle and otherwise distort. Quantitatively, the amount of wrinkling may be expressed in terms of the crustal shortening either in a specified locality or for the whole Earth. The shortening in mountainous localities is of notable magnitude. For a single mountain chain it may amount to some tens of miles. The crustal shortening for the whole Earth by thermal contraction has been calculated by Jeffreys to have been about one hundred twenty-five miles, a figure which agrees with his estimate of the observed shortening as evidenced by the displacement of formations in the world's mountain ranges. Many geologists on the basis of their own interpretation of field data have concluded that shortening afforded by thermal contraction is quite inadequate to explain the facts. Another objection that has been raised is that, because the rate of cooling of the Earth is likely to become slower as it grows older, the frequency of mountain-building eras and the magnitude of the effects should have fallen off, whereas no geologic evidence exists for a regularly diminishing activity.

Another interesting possibility is the existence of large-scale subcrustal convection. This hypothesis is based on a continuing internal mobility sufficient to permit the maintenance of thermal convection within the Earth. This hypothesis is worthy of further thoughtful consideration. It has the merit of giving an explanation to a variety of surface features; but some persons, intuitively perhaps, resist the notion of deep-seated circulation and find difficulty in imagining such processes to take place in an uniformly crystalline material such as they believe to exist throughout the mantle of the Earth. More objectively, there are mechanical details that seem difficult to work out in a satisfying way. Other theories have had other objections raised against them; and there the matter stands. An explanation of the origin of mountain chains that would satisfy both the physicist and the geologist would be a notable contribution. It seems, therefore, that this problem deserves a place high on the list of ones awaiting solution.

Origin of geosynclines--Another remarkable phenomenon, but less evident to the casual observer is the development of great depressions in the Earth's surface, which in continental areas are called geosynclines. It has long been believed that the major sedimentary deposits, the total thickness of which may amount to several miles, are due to deposition of sediments in a basin that slowly became very deep. The suggested sequence of events is the gradual subsidence of the floor of a shallow sea from the borders of which great masses of material were removed by erosion and deposited in the depression, thus forming a series of sedimentary deposits of great thickness. Later elevation of the region in subsequent ages raised the deposits far above sea level, and by folding and erosion eventually produced the well-known features of the typical mountain chain. These depressions of the Earth's surface on a grand scale have long been the subject of speculation, and much ingenuity has been applied in seeking to explain the phenomenon. It is relatively easy to account for a local upthrusting of the Earth's surface, but much more difficult to explain a subsidence. When first the reality of isostatic adjustment in the crust became established, this process was seized upon to explain the development of a geosyncline. It was said that in an initially shallow depression sediments were deposited and by their weight caused the area to sink down further deepening the depression and affording the opportunity for deposit of additional sedimentary material. This line of thought has been very productive, and there is little doubt that we may call upon the principle of isostasy to account for a significant part of the effect. What was often ignored in this connection was the really fundamental question as to how the depression started in the first place. It is, of course, possible that in an irregular or inhomogeneous crust the ever-present compression could sometimes alternate with tension, which given a favorable set of physical properties for crustal material in a certain region would cause thinning out of layers by tension and a subsequent depression. Such a process might be combined with local temperature effects producing variations in elevation from one region to another; but such supposed processes will not suffice to afford a satisfactory explanation of the great depressions, including the ocean deeps. Physically more acceptable has been the supposition of deep-seated convection on an enormous scale, whereby masses of plastic material hundreds and even thousands of miles in extent would slowly circulate producing bulges in some places at the surface and in others dragging down the upper layers to form depressions. Now, the Earth is a solid globe. Its inherent rigidity has been established by seismological observations and by other means. Nothing is more certain than that the Earth has solidity in the popular sense. On the other hand, solids under the influence of great forces are known to yield slowly by plastic deformation; and to solids as well as to liquids we may assign a definite figure for viscosity. Furthermore, the motion of a mass by convection depends not only upon viscosity and temperature but also on dimensions. The viscosity required to prevent convective agitation in a layer extending from the surface halfway down to the center has been estimated as ten to the twenty-six power cgs units--a value far greater than can be readily measured. In other words, in a layer as thick as the silicate mantle of the Earth, convective agitation could be prevented only by a viscosity considerably greater than that which applies to known solids. There is thus nothing inherently extravagant in the idea of a deep and broad circulation in the silicate mantle of the Earth.

A continuing source of heat and motive power would be provided by radioactive material, for even a minute amount of radium in the subcrustal material would supply the requisite heat; and, furthermore, experimentation with laboratory models designed to simulate what is supposed to take place in the Earth have shown in an intriguing way the development of depressions on the surface of plastic material. The major difficulty with this type of theory is to reconcile the supposed phenomenon with a variety of facts and conclusions into which it is not practicable to go at this time, except to note that an important consideration is the rate of depression throughout geologic time. Recent careful studies have indicated that the average maximum rate of crustal depression in geosynclines has increased steadily from the earliest geologic periods until the recent ones. This is evidenced by the known thicknesses of sediments for which in the Cambrian an interval of about two thousand years was required to deposit one foot, while in the Pliocene the same amount was deposited in a little over six hundred years. The rate of crustal depression may be directly related to the areal extent of eroding continental masses during the various periods, but all these processes seem to be elements of the broader picture presented to us of an Earth whose activity by some criteria is continually increasing, and in any event is not sensibly diminishing.

The problem of the origin of geosynclines is closely related to the problem of the origin of mountain-building. Indeed, geologists, noting the general association of mountains with vast sedimentary deposts that must have been laid down in geosynclines, are likely to say that we have here two aspects of one and the same problem; and going back to the dawn of geologic history, we may think of the formation of continents and ocean basins as the really fundamental problem.

The cause of igneous activity, including volcanism--Geologic history begins with the solidification of the Earth. In a globe that was originally molten, and cooled slowly and smoothly until it attained its present state of solidity, it might be expected that, except for some irregularities shortly after solidification was essentially completed, the formation of igneous rocks would have been accomplished in one brief operation, and subsequent changes in the Earth's crust limited to crustal movement, erosion, sedimentation, metamorphic processes, and chemical change. The actual situation is quite the contrary. All through geologic time, there has been a succession of periods of intense igneous activity. At intervals great outpourings of lava would issue from below the surface and spread many cubic miles of new rock over certain regions. Furthermore, from time to time masses of molten material were injected into the upper layers of the crust; and volcanic manifestations by their renewed intensity gave evidence of a hot and still active interior with no clear indication of diminishing energy. The puzzle presented here is a three-fold one. Why is the intense action confined to a series of relatively short time intervals? Why do some types of activity show a preference for certain regions of the Earth's surface? Why does the activity not taper off as the Earth grows older?

Some progress has been made in the direction of understanding volcanism. A number of years ago, when it was believed that the so-called crust was truly a solid crust floating upon a liquid interior, recurrent igneous processes were easy to explain. But measurements of earthquake wave speeds and of tidal deformation have destroyed that illusion, leaving us only isolated pockets, or thin but possibly extensive layers of molten material--if that is any comfort to us, and if we can explain the continuing liquidity of such masses. A mechanism based on a principle of physical chemistry has been offered for explaining the development of the high pressures associated with some types of volcanism. Rather vaguely some investigators have suggested ways in which heat from radioactive substances plays a role; but the broad problem of the origin and mechanism of volcanoes remains unsolved.

Origin of deep-focus earthquakes--Most earthquakes originate at depths no greater than that associated with the average thickness of the Earth's crust. Seismograph records of such earthquakes show the surface waves, which are ones that simply follow along the surface layers, and the "through" waves, of both the longitudinal and transverse variety, that follow along curved paths through the Earth from focus to instrument. Such quakes admit of ready explanation. The vibrations quite evidently are those caused by a jarring impulse, such as could accompany the sudden yielding to stress in the Earth's crust. Now the thermal contraction of the Earth, which has already been referred to, would gradually build up stress; and, whether or not the amount of this stress is sufficient to account entirely for large-scale crustal movement, its magnitude is very considerable; and in any layer that possesses finite strength the stresses will accumulate until the limit of strength is reached, whereupon fracture or movement will suddenly occur, initiating a shock, relieving the stress, and starting afresh a new cycle of similar events.

So much for the more usual type of earthquakes, which originate at depths commensurate with the thickness of the crust. But roughly ten per cent of all shocks are known to be initiated by some disturbance at much greater depths, amounting at times to as much as four hundred miles. The special characteristics of such shocks are that they show nearly uniform intensity over a wide area but with little surface damage, and that on the seismograms there is no clear evidence of surface waves, especially at long distances.

The difficulty in finding a ready explanation for deep-focus earthquakes has a two-fold basis. First, such earthquakes originate at depths where the material of the Earth is by any theory close to its melting point, and, therefore, very hot; and, second, because of the relatively small amount of stress that could be developed by the simple process of thermal contraction at such relatively great depths. An attempt has been made to get around these difficulties by postulating in the hot material the right kind of plasticity for the material to exhibit strength for limited periods of time, and by assuming certain volume changes due to transformations in the slowly cooling material. The substance of the Earth from the bottom of the crust to the top of the iron core, according to a simple Earth model that is gaining favor, consists almost entirely of dunite--that is to say, of olivine (magnesium iron orthosilicate). We may think, then, of two crystalline forms of olivine--one stable at pressures less than those corresponding to certain depths, and the other at the greater depths and pressures. The transformation pressures will depend upon temperature. Furthermore, the crystalline form stable at the higher pressures will have the smaller volume, that is, the greater density. As the Earth cools the depth marking the boundary between the two crystalline forms would move up or down depending upon the relative slopes of the temperature-depth curve and of the temperature-pressure transformation curve. In a layer adjacent to the initial boundary zone, the material would be slowly changing from one form to the other with consequent volume change that locally would build up elastic stresses. Such a phenomenon, even if its reality were established, would leave certain features of deep-focus earthquakes to be explained--for example, the presence of such shocks for limited areas of the Earth's surface. But the suggested mechanism is an intriguing one, and points up the value of investigating the high-pressure phases of silicates at pressures something like a hundred thousand atmospheres. For the practical application of such experimentation, the pressures of this magnitude would need to be combined with temperatures of over a 1000° C. The carrying out of such measurements is a difficult task, but the results would be of unusual interest and value.

Origin of the Earth's magnetic field--The Earth is a magnet--a relatively weak one considering its size, but one that gives rise to a variety of interesting effects. The source of the Earth's magnetic field has long been a subject of speculation. It has been determined that ninety-four per cent of the permanent magnetic field arises from causes within the Earth, but an entirely satisfactory basis for the internal magnetism is still wanting. Oddly enough, the existence of a massive iron core within the Earth does not help us, for iron and high-iron alloys lose their magnetic quality completely at temperatures of only a few hundred degrees, and the interior of the Earth on any reasonable hypothesis is measured in thousands of degrees. It was thought at one time that pressure might have a significant effect in raising the temperature at which transformation takes place--that is, the Curie point--and that the intense pressures existing in the interior, amounting to hundreds of thousands and even millions of atmospheres, might raise the Curie point to an extent sufficient for at least a part of the iron core to retain its ferro-magnetism. However, what experimentation has been carried out with iron on the relation between Curie point and pressure has failed to indicate any change whatever. Incidentally, this may be considered a consequence of the circumstance that in iron the transformation from the magnetic to the non-magnetic state takes place without change of volume. No comfort is afforded by turning to magnetite--an oxide of iron common in basic rocks and possibly existing in considerable quantities within the Earth. Magnetite has a Curie point even lower than that of iron; and experimentation--at moderate pressures, to be sure--reveals no effect of pressure. The matter cannot be considered as settled, because pressures higher than the existing practicable range for experiments and particularly the extreme pressures corresponding to those in the far interior, might give rise to unpredicated effects. Furthermore, the reality of a change of Curie point with pressure for some substances is indicated by recent unpublished measurements on an iron spinel.

A variety of other explanations has been put forth to account for the Earth's magnetic field. According to one of these, electric currents within the Earth are supposed to make the Earth a huge electromagnet. This hypothesis is based on the fact that an electric current, if once started in a copper sphere the size of the Earth, would die down with extraordinary slowness, retaining half its initial value after a lapse of three billion years. The obvious objections to this hypothesis are, first, the difficulty of imagining how such a current would start, and, second, the high resistivity of the Earth's mantle as compared with that of copper.

Another hypothesis was suggested by the discovery of the Sun's magnetic field, and is based upon a supposed internal circulation of the material within the Earth, the circulation inducing electric currents and consequent magnetic fields which are built up by a process of self-excitation. The immediate objection here, of course, is the improbability of sufficiently low viscosity, in any considerable part of the Earth, to permit fluid motion of the kind that has been supposed.

A favorable outlook for solving this great problem would seem to depend on either finding a way by which common ferro-magnetic materials can retain their magnetism at high temperatures or by discovering some hitherto unsuspected mechanism for obtaining a magnetic field.

Temperature of the interior--The thermal history of the Earth starts with its formation, concerning which there remains divergence of opinion as to details, although there is now general agreement that the substance of the Earth, as well as the other planets, was originally a part of the Sun, and was drawn off by some disruptive action due to the close approach of another star. According to the favored view concerning the origin of the Earth, the separated mass quickly became a liquid globe in which the metallic part settled to the bottom, after which it solidified and then underwent further cooling by thermal conduction, the latter process in bodies of large size being an extremely slow one. Indeed, by any variation of the theory concerning the cooling of the Earth, the temperature in the center out to a point a few hundred miles from the surface is not essentially different from what it was at the time fo the Earth's formation.

From measurements of temperatures in deep bore holes and from determinations of the radioactive content of crustal rocks, we can obtain a useful, although not completely satisfactory, notion of the temperatures that now prevail in the crust and for some distance beneath it. One of the serious gaps in our knowledge--and the principal factor that impedes further progress in several lines of investigation concerning the interior, is our inability to form a satisfactory notion of internal temperatures. It is a curious fact that, whereas we know the central pressure with great precision--it is 46,500,000 pounds per square inch--the estimates of temperature at great depths are hardly more than wild guesses. To be sure, some limits have been established. The temperature is not likely to be higher than the temperature of the Sun's surface--say, 6000°C--and it is not likely to be lower than the melting point of refractory rocks, making some allowance for the effect of pressure--say, 2000°C. A favored figure of the internal temperature, as it has been used by geophysicists, is 3000°C but this cannot be regarded as more than a guide to thinking.

The problem of the Earth's central temperature is obviously not to be solved by experiment alone. As with other factors relating to the nature of the interior, we need converging lines of evidence, and particularly the benefit of theoretical investigations.

Concluding remarks--I have outlined six problems in geophysics: (1) Origin of mountain chains; (2) origin of geosynclines; (3) basic causes of igneous activity including volcanism; (4) origin of deep-focus earthquakes; (5) origin of the Earth's magnetic field; and (6) temperature of the interior. But there are many other matters of deep significance that invite serious attention. The present selection admittedly is somewhat arbitrary. It is more than likely that the ones that have been mentioned are not in all respects the most important. Possibly every reader of this article will have elevated his eyebrows in mild protest at the apparent neglect of his favorite line of investigation or the omission of his pet problem. The ones selected here are merely those that appear to the writer to be particularly baffling; they will, perhaps, serve to emphasize the opportunity that the investigator of the present and future has for increasing our understanding of the Earth as a whole by providing partial or complete solutions to the great unsolved problems.

It is evident that an outstanding need for further progress is in general more facts in all the departments of geophysics, not neglecting research on the properties of matter. Inasmuch as the greater part of the Earth is silicious in composition, we particularly need much more information on the behavior of silicate mixtures--their melting relations and their physical properties, not only under the conditions that prevail during the geologic processes taking place in the crust but also, to the extent that can be found practicable, at the temperature and pressures corresponding to the deeper parts of the Earth. It has begun to be appreciated that the key to an understanding of the accessible part of the Earth lies in the far interior, the composition and plasticity and temperature of which are still hardly more than matters of conjecture. There are those who believe that the brightest hope for the future is intensive research on the properties of atoms and molecules exposed to extreme pressures. For this, the theoretical physicist must bring forward his sharpest tools.

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Transactions, American Geophysical Union Volume 28, Number 5 October 1947

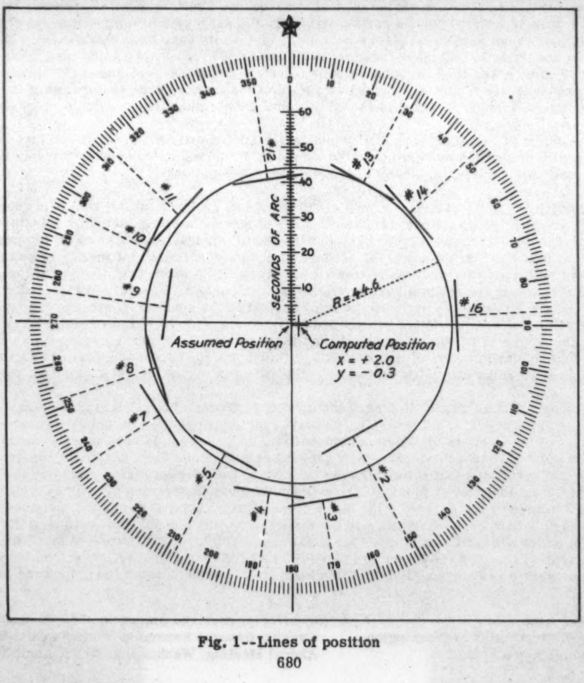
GEOGRAPHICAL POSITIONS BY SOLAR OBSERVATIONS

G. Leifson and W. T. Therrell

Abstract--This paper presents the results and methods employed to obtain a geographical position in the polar regions from measured zenith distances of the sun during periods of continuous daylight.

Introduction--In connection with a recent visit by United States Naval Hydrographic Office personnel to areas north of the Arctic Circle, it was planned to observe a number of astronomical positions mainly for the purpose of checking the horizontal datum of existing Hydrographic Office charts and maps of the region. The only means of transportation available was by water, and since ice conditions precluded visiting these areas except during the middle of summer, it was necessary to plan the program of observations for a period of continuous daylight.

Plan of observations--After some preliminary studies, the following observing program was decided upon: Measure the zenith distances of the Sun and Venus with one hour intervals between sets for a period of 18 to 24 hours by means of a light WILD T2 theodolite fitted with a solar eyepiece. In case of the Sun, measurements were to be made in rapid succession on each limb with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10
SECONDS OF ARC
R = 44.6
#2
#3
#4
#5
#7
#8
#9
#10
#11
#12
#13
#14
#16
Assumed Position
Computed Position
X = + 2.0
y = - 0.3

Fig. 1--Lines of position

the telescope direct and reversed. To insure accuracy in timing, a break-circuit sidereal chronometer, chronograph, and radio for time signals were to be employed. The theodolite was to be supported on a rigid stand or iron pipe embedded in concrete and a windshield to be rigged if and where necessary. All the observations at one place were to be made by the same observer to avoid introducing a different personal equation during the program.

Actual observations--Because of time limitations, unfavorable weather, and the many varied duties assigned to the observer on this expedition, it was not possible to carry out the program as planned. Radio time signals could not be received on the portable sets owing to electromagnetic disturbances possibly caused by sun spots, so the accuracy of timing the observations depended on correcting for the error and assumed rate of the chronometer. No observations on Venus were made. The 13 sets of solar observations were made from a tripod set-up, without windshield, using the WILD T2 theodolite as planned.

Computations and results--The computations were accomplished by the conventional methods similar to stellar observations using the mean time and zenith distance for each set. The observed mean zenith distances of the sun were corrected for refraction by the table on page 59, U. S. Coast and Geodetic Survey, Special Publication No. 14, and, for the sake of convenience in plotting, a constant of +50″ added to each. The differences between the observed and computed zenith distances are shown as lines of position on Figure 1. The customary least squares adjustment was made to determine the most probable correction to the assumed position (see Fig. 2).

Remarks--Perhaps it is fortunate that the original plan of observation was not carried out since the results as shown on Figure 1 now represent what can be expected from solar observations in Arctic areas, without the aid of any special equipment or refinement in observation technique. The lines of position shown have a maximum variation from the mean of 8″ and the position a probable error of 0″.8 using the common formula for probable error. The observer's personal equation and the deflection of the vertical are of course the unknowns in the geodetic accuracy of the position.

STAR (Number)	AZIMUTH	SINE x= +1.965	COSINE Y= -0.326	-Z R= 44.60	Σ.	• •m.= 3.38"
13	28	+0 470	+0 883	-45 1	-43 747	+0 13
14	48	743	669	-47 0	-45 588	-1 16
16	87	999	+ 052	-48 6	-47 549	-2 06
2	151	485	- 875	-36 5	-36 890	+9 34
3	170	+ 174	985	-50 8	-51 611	-5 54
4	188	- 139	990	-48 6	-49 729	-3 95
5	208	470	883	-41 6	-42 953	+2 36
7	236	829	559	-46 3	-47 688	-3 15
8	252	951	- 309	-41 4	-42 660	+1 43
9	277	992	+ 122	-36 7	-37 570	+5 91
10	296	899	438	-46 9	-47 361	-4 21
11	313	731	682	-44 8	-44 849	-1 86
12	351	- 156	+ 988	-41 2	-40 368	+2 77
i		-0 63681	-0 21271	-159 61501	-160 46451	
Σ (excluding i)		-2 296	-0 767	-575 5	-578 563	
		p.e. 0.6745 = $\sqrt{\frac{220.37}{13\times12}}$ = 0.8"				
n = 13						
$\sqrt{\frac{1}{n}}$ = 0.2773501		Σ (sin²) +5 8138	Σ (sin.cos) +0 3752	Σ (-Z.sin) -11 0469	Σ (Σ_0.sin) -4 8579	
		x =	-0 06455	+ 1 90013	+0 83558	
Each-i expression is equal to $\sqrt{\frac{1}{n}}$ ×			Σ (cos²) +6 7363	Σ (-Z.cos) +1 4742	Σ (Σ_0.cos) +8 5857	
(sum of column)-i, in which-i = $\sqrt{-1}$			+6 7121	+2 1872	+8 8993	
and -i^2 = -1, n = number of stars.			Y =	-0 32586	-1 32586	

Fig. 2--Example of least squares computation of most probable correction to the assumed position

The consistency of the lines of position are considered remarkable since similar attemps at position fixing in lower latitudes have generally proven to be inaccurate and inconsistent. The point in favor of the polar regions is, of course, the fact that observations can be taken on the sun in all azimuths. The sun varies little in altitude and the atmosphere is quite uniform so that tables of refraction apply with consistent precision.

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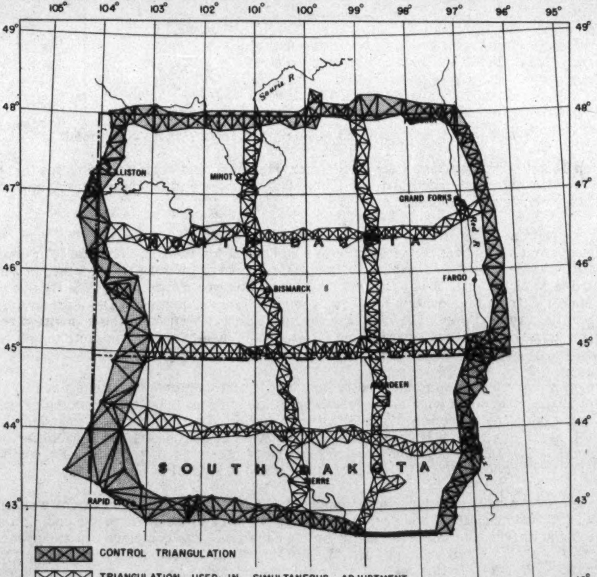
SIMULTANEOUS ADJUSTMENT OF MULTIPLE ARCS OF TRIANGULATION

Leslie E. Shmidl

Abstract--This paper explains the method used to adjust the arcs of triangulation in North and South Dakota by simultaneous adjustment. The least-squares adjustment of 836 equations and 1913 v's or corrections was accomplished with no serious difficulty and gave satisfactory corrections.

As the adjustment of the triangulation networks in the United States progresses, the arcs and areas become increasingly smaller, allowing less leeway in distributing the corrections from the individual adjustments. This general procedure results in a tendency for the corrections to increase until in some localities, where observing conditions may be unfavorable, the corrections become larger than normally expected from the experience of the United States Coast and Geodetic Survey.

An area including most of North and South Dakota has been crossed by three east-west arcs and two north-south arcs of triangulation. These new arcs are within a loop that was a part of the readjustment of the triangulation in the western half of the United States (see Fig. 1). Rather than adjust these arcs individually and thus divide the areas by successive adjustments, it was decided to make a simultaneous adjustment of all the arcs.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GRAND FORKS
Red R
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FARGO
BISMARCK
ABERDEEN
S O U T H D A K O T A
PIERRE
RAPID CITY
CONTROL TRIANGULATION
TRIANGULATION USED IN SIMULTANEOUS ADJUSTMENT

Fig. 1--North and South Dakota triangulation adjustment

After a preliminary check of the triangles had been made to insure that the average triangle closure did not exceed one second and that the discrepancy of the sides did not require more than an average of 0."4, sketches were drawn in 23 parts. The parts consisted of 17 sections or arcs of triangulation, and six junction figures. The junctions were formed by the intersections of the various sections. Four bases and 13 Laplace azimuths had been determined and were included in the adjustment. For simplicity and as an added precaution in order to avoid confusing the various sections and junctions, each section was lettered and each junction numbered (see Fig. 2). After drawing the sketches showing the relative positions of the stations, the directions were numbered. The numbers ran consecutively through each of the 23 parts.

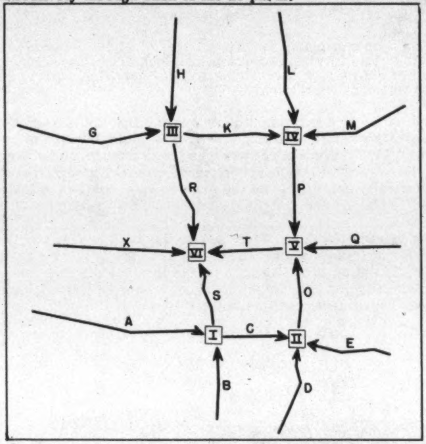

Fig. 2--Arcs and junctions of North and South Dakota adjustment

The angle and side equations were written for each part as a complete unit. As these equations followed the standard practice of the United States Coast and Geodetic Survey and other agencies, they require no comment.

Length equations were written for various lettered sections to a common line in the junctions. If a Laplace azimuth was part of the junction it was chosen for the common line. For example, the length equation in Section D was written to Line Bald-Grove of Junction II; likewise, in Section E to Bald-Grove of Junction II. The complete length equation would then be D - E. By subtracting the equation for E from the equation for D the complete length equation of D + E is written for the full length of the two sections. The E part of the equation was written in the opposite direction of the complete equation, and thus substraction reverses the signs and the complete length equation is derived. Extra length equations were written for the four bases.

The preliminary triangles to be used in the latitude and longitude equations were written using the same traingles that were used in the length equations. From these triangles the preliminary positions were computed to common points in each junction: Sections A and B to station Van Wold of Junction I; Sections (B + C), D and E to Bald of Junction II; Sections G and H to Hoffer of Junction III; Sections (H + K), L, and M to McHenry of Junction IV; Sections (L + P), (D + O), and Q to Elden of Junction V; and Sections (B + S), (H + R), (Q + T), and X to Wolf of Junction VI.

After the preliminary positions were computed, the 24 azimuth equations were written. The latitude and longitude equations were written through the various sections to the common station in a junction and differences taken for the complete equation. The complete equations were B - A, (B + C) - E, D - E, H - G, (H +K) - M, L - M, (L +P) - Q, (D + O) - Q, (B + S) - (Q + T), (H + R) - (Q + T), and X - (Q + T). In this method of writing the latitude and longitude equations, each time a section was used it had the same algebraic sign. For example, Section Q was used five times in the equations and each time it was used it was - Q. By using a section with the same algebraic sign, the computation of the normal equations and forward solution required less work and the chances of compensating errors were reduced. The complete adjustment required 836 equations and and 1913 v's or corrections.

The correlate and normal equations for the 23 parts were set up. Extra checks were made to insure that the closure term was used properly as some equations extended through a number of sections. Normal equations for each part were computed as a complete unit, even when only part of an equation was in that section. These separate parts were combined however when the forward solution was computed.

The forward solution computation started from the ten terminals of the outside sections running to the various junctions. In this way ten computers could have been used on this solution at one time. After the junctions were reached, one computer combined the sections, computed the junction and computed to the next junction. For example, Sections A and B were combined in Junction I and the computation carried across Section C to Junction II which had combined Sections D and E. The various sections were computed as shown in Figure 2 until the last equations werre solved in Junction VI.

The solution of the longer equations was simplified by dividing the series of multiplications into smaller groups. A check was obtained on each group before it was combined into the solution. This process has become known as an accumulation method. No additional multiplications were required but the additional checks obtained made possible the solution of extremely long series of multiplications. This also allowed two or more computers to work on a single section at one time.

The back solution and computation of v's followed regular practice and is fully explained in various special publications of the United States Coast Survey.

The 1913 v's or corrections to the directions as computed by this adjustment were satisfactory. The average correction was 0."54 with a probable error of ±0."58. The averages for each section are given in Table 1.

Table 1--Average corrections for each section

Section	No. of v's	Average v	Maximum v
		"	"
A	130	0.49	1.55
B	72	0.55	2.53
C	68	0.45	1.58
D	86	0.38	1.46
E	69	0.72	3.76
G	120	0.42	1.58
H	109	0.48	1.96
K	113	0.48	2.21
L	113	0.56	1.64
M	104	0.37	1.34
O	83	0.47	1.73
P	97	0.54	1.48
Q	127	0.50	2.06
R	123	0.53	2.58
S	66	0.44	1.55
T	94	0.57	1.60
X	121	0.70	3.53

In the consideration of this problem, two questions may be asked. First, are the results as good or better than the usual methods of adjusting by single arcs? Second, do the results justify the extra cost of a simultaneous adjustment? As compared with other triangulation adjusted by the United States Coast and Geodetic Survey, the average corrections and probable errors agree favorably with single arc adjustments, but the simultaneous method has the advantage of distributing the discrepancy over a larger area and thus reducing excessive corrections. The extra cost involved was very small. This adjustment required about 5000 hours or 28.8 man-months. A report based on previous records states that the solution of 1800 equations in various adjustments required 60.4 man-months. At the same rate, the North and South Dakota adjustment by single arcs would require 27.9 months. The mathematicians assisting with the North and South Dakota adjustment were above the average in ability and experience, and their cooperation and industry, which are to be commended, reduced the number of hours required for the adjustment. A fair estimate, would be that a simultaneous adjustment would require between 10 to 15 per cent more time to complete than the adjustment of the same arcs by the single arc method. The maximum size of an adjustment that is practical is a difficult point to decide. However, it is estimated that adjustments by simultaneous methods of 1000 to 2000 equations would not be impractical.

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THE OZARK EARTHQUAKE OF OCTOBER 8, 1946

Ross R. Heinrich

Abstract--On October 8, 1946 an earthquake was felt throughout an area of about 25,000 square miles in eastern Missouri, western Illinois, and northwestern Kentucky. The data obtained from 691 questionnaires returned show that: (1) The shock was felt over a wide area but was not of destructive intensity; (2) the felt area as a whole was almost circular in shape; (3) the region of stronger intensities was eccentric to the total felt area, being toward the south; (4) near the epicenter the earthquake noises were described as sharp and of short duration while at greater distances the noises were described as rumbling and of long duration. The epicenter determined from seismographic data is in southeastern Iron County about midway between the towns of Chloride and French Mills, Missouri (37°28'N, 90°34'W; H = $01^h12^m02.5^s$ U. T.). This point is roughly 50 miles northwest of the New Madrid seismic district. The epicenter is in the vicinity of the Hogan fault which is postulated as delineating the southwest side of the structural block of the St. Francois Mountains (the major structural and physiographic unit of the northeastern Ozark Highlands).

Introduction--The local earthquake which occurred in the Ozark Highlands of Missouri on October 8, 1946; 01^h12^m U. T., has furnished some interesting data on the Mississippi Valley earthquake problem.

Examination of the available seismic data for the Middle Mississippi Basin had led the author to speculate recently regarding the relatively aseismic character of the Ozarks of Missouri, that is, to question whether the Ozark Plateau was a region free of local earthquakes surrounded by zones of seismic activity. This line of speculation had been aroused by two kinds of evidence. In the first place, up to that time there were no definite instrumental or noninstrumental records of earthquakes which originated in the Ozarks. Secondly, the author's geological reasoning was guided somewhat by the prevalent theory of Ozark structure which explicitly or implicitly has considered the Ozark Highlands to be a simple geanticline produced by a dominantly vertical uplift.

The earthquake of October 8, 1946 presents conclusive evidence that shocks originate near the topographic crest of the Missouri Highlands and suggests a possible interpretation of some of the older seismic data. Moreover, this earthquake shows significant relationships to geological data which would tend to indicate the importance of faulting in the basement structure of the Ozarks.

Non-instrumental data--A postcard-questionnaire survey was conducted in the affected region immediately after the earthquake. Six hundred and ninety-one cards were returned in this survey. Their distribution by states is shown in Table 1.

Table 1--Distribution of returned cards

State	Felt		Not felt	Total
	Counties	Cards		
Missouri	32	231	293	524
Illinois	14	60	78	138
Kentucky	2	2	13	15
Tennessee	0	0	14	14
Total	. .	293	398	691

The data from the 293 felt reports were evaluated according to the Modified Mercalli intensity scale of 1931 and the results were plotted on the isoseismal map of Figure 1. We might indicate a few pertinent details.

Although the points at which the earthquake was felt were scattered widely, there was no conclusive evidence of damage. Three isolated reports should be mentioned. There was one report of an overturned vase near Bates and Delor streets in the south part of St. Louis, a pendulum clock was stopped at 01:13 (U. T.) at Greenbriar Country Club west of St. Louis, and pictures were reported knocked from a wall at Eminence, Missouri.

With the exception of these three cases, the reports were chiefly observations of the character of the vibrations and the earthquake noises. It seems reasonable to evaluate the maximum intensity of this shock as 4, that is, bordering on the destructive.

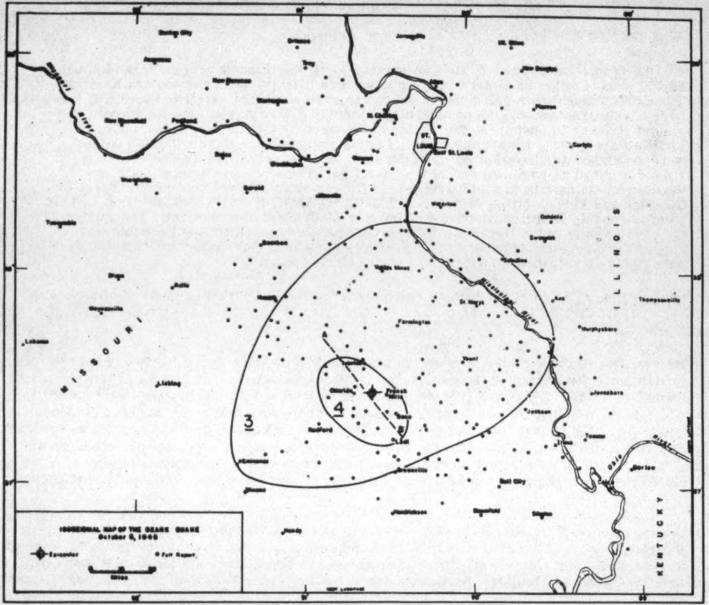

Fig. 1--Isoseismal map of the Ozark earthquake of October 8, 1946

In preparing the isoseismal map the zones of 4 and 3 intensity were delineated, but the zones of 2 and 1 were not separated because of the heterogeneous distribution of the reports (especially the unbalance of the St. Louis metropolitan area) and because of the inability to compensate for the varying influence of local geology.

The isoseist 4 which defines the epicentral region is elliptical with the major axis trending northwest-southeast. This region is contained in parts of Iron, Madison, Reynolds, and Wayne Counties, Missouri. Typical descriptions of the shock in the epicentral region are the following.

Myrtle Ruble of Vulcan, Iron County, stated, "It sounded like low, heavy thunder and then a long rumbling noise in the distance...it just seemed to pick the house up, shake it, and set it back down." Mrs. Villa R. Harris, Annapolis, Iron County, commented that the earthquake had "a rumbling and noise like an explosion underground." George Kemp of Saco, Madison County, wrote that the earthquake "was felt by all in the community . . . it was like an explosion of dynamite, then a roaring like thunder and seemed to raise the building . . . It lasted about eight to ten seconds." In Lodi, Wayne County, G. H. Rainwater noted that "at first it felt like a big motor started underground with a vibration." Hattie B. McKibbin of Lesterville, Reynolds County, described the shock as "a sharp concussion followed by a distinct roar-like thunder."

The zone defined by the isoseist 3 shows several interesting points. The zone itself is in general elliptical but the major axis of the ellipse is almost at right angles to the major axis of the epicentral region. Mrs. Howard Hahn of Yount, Perry County, remarked, "The sheet-iron roof rattled. It seemed as if something bumped the house." William H. Smith described the shock at Festus as "a constant rumbling which began with a sound as if a heavy train were approaching. The noise increased in intensity until finally the doors and windows were shaking terrifically." Just on the border of this zone toward the north, Donald H. McInnis, a fourteen year old boy of Huzzah, Crawford County, made the interesting report that "the rest of the family, standing on the first floor, heard a rumble like an airplane but felt no quake . . . I was lying down in bed on the second floor, my feet pointing south, it seemed as if some invisible force had given me, the bed, and the house a gentle push."

Within the metropolitan area of St. Louis the earthquake was reported erratically. There were many places where the earthquake was felt and many places where it was unnoticed. To be specific the author who was in the western suburbs did not feel the shock but one of his colleagues who was in the southeastern part of the city stated the vibrations were quite noticeable.

Instrumental data--Table 2 contains a summary of the instrumental data obtained from the original seismograms of the Cincinnati, Florissant, and St. Louis Stations. The interpretations of the phases listed in Table 2 are based on the Walter-Birkenhauer travel-time tables for the east central United States. An interesting feature of the St. Louis records is the three distinct phases which were recorded between the P_1 and S_1 phases. At the present time no interpretation of these phases is attempted.

Table 2--Instrumental data (epicenter 90°34′W, 37°28′N; time $01^h12^m02.5^s$ U. T.)

Station	Wave	Time (U. T.)			Remarks	
		h	m	s		mi
St. Louis	iP_3 (P_2)	01	12	24.7	... ...	...
	iP_1		12	25	... ...	...
	i (?)		12	28	... ...	...
	i (?)		12	29.9	Distances P_3-H	82.7
	i (?)		12	34.5	Distance Calc	82.5
	iS_1		12	39	... ...	...
	iS_3		12	40	... ...	...
Cincinnati[a]	iS_3	01	14	24.7	Distance S_3-H	349.3
	iS_0		14	41.9	Distance Calc	349.5
Florissant	S_3 - P_3, 17.1 sec	..	...	...	Distance S_3-P_3	93.4
					Distance Calc	92.6

[a] Records by courtesy of V. C. Stechschulte, Xavier University, Cincinnati, Ohio

The epicenter determined from these data is in southeastern Iron County about midway between the towns of Chloride and French Mills, Missouri in the zone of maximum intensity defined by the macroseismic data.

Geology of the region--The Ozark Highlands of Missouri rise to a crest within the area defined by isoseist 3. Taum Sauk Mountain, the highest point in Missouri, is within the epicentral region, about 12 miles northwest of the instrumentally-determined epicenter. The igneous basement of the area consists of Pre-Cambrian intrusive granites and extrusive felsites. The surface of these Pre-Cambrian rocks was thoroughly eroded to produce great relief prior to the deposition of the overlying Paleozoic sediments--Cambrian and Ordovician dolomites, sandstones, and shales. Erosion of the present surface has uncovered the igneous rocks at many places in the region so that outcrops of Pre-Cambrian granite and felsite are interspersed among the outcrops of Paleozoic sediments. The isoseist 3 roughly outlines the region of igneous outcrops.

Physiographically this region has been designated as the St. Francois Mountains unit of the Ozark Highlands. The epicenter is near Marble Creek which is one of the tributary streams of the St. Francis River watershed.

The general structure which has been proposed for this region is one of a dome reaching an apex in the main igneous exposures with the sediments arching over the dome with slight dips toward the west and steeper dips toward the east. Many investigators have considered the Ste. Genevieve fault a major structural feature of the region. This fault described by WELLER and ST. CLAIR [see "References" at end of paper, 1928] occurs in the Paleozoic rocks east of the St. Francois Mountains, more or less paralleling the Mississippi River. MOSS [1936] suggested that this fault zone also extended into the buried Pre-Cambrian basement.

GRAVES [1938] made an attempt to interpret the Pre-Cambrian structure of Missouri by means of fault blocks. One such block which he suggested was the St. Francois Mountains block. He based his conclusions on an investigation of the observed relations of the Pre-Cambrian rocks; faults in the Pre-Cambrian rocks; faults in the Paleozoic cover; alignment of structural and physiographic features; and the locations of granite intrusions, dikes, and zones of mineralization.

Some of his statements which refer to the epicentral region of this earthquake should be quoted. After examining the evidence in favor of a down-dropped block in the Belleview Valley northwest of Ironton, Missouri, he noted that the line defining the southwest side of the Belleview block passes through a granite outcrop near Hogan. This granite is outside of the main area of outcrop, "suggesting a fault striking northwest through the whole St. Francois Mountains Block. This assumed fault along this line may be called the Hogan fault . . . Southwest of Coldwater there is an area of granite . . . A shear zone in this granite strikes north-south and is probably due to faulting. The granite has been mineralized, the solutions apparently following the north-south shear zone. A basic dike 20 feet in width strikes N 45° W and may follow a fault. Southeast of this granite are two small outcrops west of Bear Creek. A line drawn through these outcrops would pass through the granite near Hogan, thus suggesting that the granite lies on a continuation of the Hogan fault."

This postulated fault zone passes directly through the epicentral region of the earthquake of October 8, 1946, as indicated on Figure 1 by the dashed line AB.

Previous earthquakes--Examination of data on the seismic history of Missouri [HEINRICH, 1941-1946] reveals several earthquakes which may have originated in the region. A single shcok was reported at Ironton on July 28, 1882. At 06^{h} on February 15, 1884 a tremor of three or four seconds duration was reported at Caledonia. On October 4, 1903 an earthquake was felt strongly in the lead belt district south of St. Louis at 20^{h}56^{m}. This may have been on the Ste. Genevieve fault. July 4, 1907 at 03^{h}00^{m} a tremor was felt at Bismarck, Missouri, "Many people in the Arcadia Valley felt the earth shocks . . . preceded by a low, long rumbling, not unlike thunder." On February 26, 1929 a local disturbance accompanied by a rattling noise was felt at Arcadia, Missouri at 02^{h}15^{m}.

Summary--What then have we learned from this study of the Ozark earthquake of October 8, 1946?

The isoseismal data show that the earthquake, although of moderate surface intensity, was felt rather widely. This is a feature common to many of the earthquakes in the Middle Mississippi Valley. It has been advanced in some quarters as evidence that earthquakes of this type originate at the base of the mantle or deeper.

Surface geology affected the felt intensity of this earthquake. The area defined by isoseist 3 was apparently controlled by the presence of Pre-Cambrain igneous rocks at or near the surface. The spotty character of the intensity outside of this zone shows effects of surface geology as well as other factors such as difference in population density and incompleteness of the questionnaire survey.

The location of the epicenter of the earthquake shows that earthquakes do originate in the St. Francois Mountains the topographic crest of the eastern Ozark Highlands, Moreover the position of the epicenter is additional evidence in favor of the Hogan fault zone which may be an important feature of general Ozark structure.

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RESPONSE CHARACTERISTICS OF SEISMOGRAPH AT THE UNIVERSITY OF TEXAS

D. S. Hughes

Abstract--The horizontal pendulums of the seismograph at the University of Texas have been equipped with McComb-Romberg "pick-ups." Instead of recording directly, the light from the pick-up mirror falls on a split photo cell; the current from this photo cell is amplified and sent through the recording galvanometer. The output of the amplifier is also fed to an auxiliary circuit which controls the intensity of the recording light so that its brilliance is approximately proportional to the speed with which the galvanometer spot is moving.

The McComb-Romberg pick-up involves viscous coupling between the seismograph beam and the remainder of the system. A method of measuring the magnification at all relevant frequencies is described.

The seismograph at the University of Texas, at present, consists of two horizontal pendulums. The beams are ten feet long with masses of about 200 lbs. These can easily be set to and maintained at a free period of 50 seconds; however, so far a period of about 35 seconds has been used. Because of its freedom from zero shift, it was decided to use the McComb-Romberg pick-up and in order that a common drive system might be used for the recording drums of both horizontal components and a projected vertical component, an electronic recording system was devised.

The pick-up is shown in Figure 1. A small rectangular oil tank is mounted on the end of the beam. The mirror is fastened to a vertical suspension with an eccentric vane dipping into this tank. Motion of the oil swings the mirror. At intermediate frequencies the angular magnification is roughly the ratio of the beam length to the eccentric offset of the vane from the suspension.

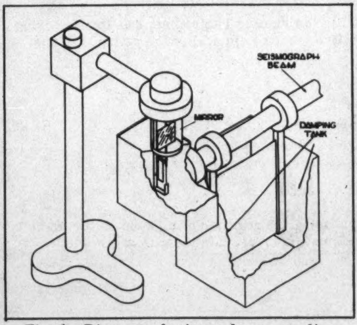

Fig. 1--Diagram of mirror-beam coupling

At very low frequencies, the viscous drag is insufficient and the mirror does not follow the motion, the magnification decreases and for very slow motion is essentially zero. Thus the mirror does not follow the zero shift of beam. At very high frequencies the moment of inertia of the mirror is not negligible and the magnification decreases to zero. Thus the magnification must be measured at several frequencies in order to adequately describe the behavior of the instrument.

A horizontal pendulum with oil damping may be considered as a simple harmonic oscillator with damping proportional to the velocity of motion. If q_1 is the displacement of the beam in an inertial system and Q is the displacement of Earth, the equation of motion is

$$mq''_1 + 2b(q'_1 - Q') + c(q_1 - Q) = 0 \quad \ldots \quad (1)$$

where m is the inertia, 2b is the damping constant, and c is the restoring constant.

Substracting mQ'' from each side of the equation and replacing $q_1 - Q$ by x, the equation becomes

$$x'' + 2\mu x' + k^2 x = -Q'' \quad \ldots\ldots\ldots\ldots \quad (2)$$

where $\mu = b/m$; $k^2 = c/m$, and x is the displacement referred to the Earth.

For a sinusoidal motion of the ground

$$Q = A \sin \omega t$$

and

$$x = R \sin (\omega t - \Phi) \qquad (3)$$

where

$$R = A\omega^2/\sqrt{(k^2 - \omega^2)^2 + 4\mu^2\omega^2}$$

$$\Phi = \tan^{-1} 2\mu\omega/(k^2 - \omega^2)$$

If a sinusoidal force is applied to the beam the equation of motion is

$$x'' + 2\mu x' + k^2 x = F \sin \omega t \qquad (4)$$

and

$$x = Q \sin (\omega t - \Phi) \qquad (5)$$

where

$$Q = F/\sqrt{(k^2 - \omega^2)^2 + 4\mu^2\omega^2}$$

$$\Phi = \tan^{-1} 2\mu\omega/(k^2 - \omega^2)$$

Thus the constants μ and k which determine the response to ground motion can be determined by measuring the response of the beam to an applied sinusoidal force of constant amplitude at various frequencies and finding the values that give the best fit to the observed curve. Ordinarily, of course, these constants can be determined by simpler procedures.

The equation of motion of the pick-up is

$$I\theta'' + 2d\theta + e\theta = 2d\ell x'$$

where I is moment of inertia of mirror and vane, 2d is the viscous resistance, e is the restoring constant of the suspension, and ℓ is a constant, effectively the reciprocal of the distance of the center of the vane from the suspension.

This equation may be written

$$\theta + 2p\theta' + r^2\theta = qx' \qquad (6)$$

where

$$p = d/I;\ r^2 = e/I\ q = 2d\ell/I$$

Rigorously (2) and (4) should contain terms expressing the reaction of pick-up on the main beam; because of the relative masses of the two systems, however, this term is negligible.

For an applied sinusoidal force from (5)

$$x' = \omega Q \cos(\omega t - \Phi)$$

Substituting in (6) and solving

$$\theta = P \sin (\omega t - \Phi + \psi) \qquad (7)$$

$$P = q\omega Q/\sqrt{(r^2 - \omega^2)^2 + 4p^2\omega^2}$$

$$\psi = \cot^{-1} 2p\omega(r^2 - \omega^2)$$

or

$$P(\omega)/Q(\omega) = q\omega/\sqrt{(r^2 - \omega^2)^2 + 4p^2\omega^2} \qquad (8)$$

Thus if the amplitude P of the angle θ and Q, the motion of the beam are determined at several different frequencies, the constants p, q, and r which characterize the pick-up can be determined and thus the over-all response to Earth motion.

From (7) and (3) the motion θ for a sinusoidal Earth motion is

$$\theta = [A\omega^2/\sqrt{(k^2 - \omega^2)^2 + 4\mu^2\omega^2}][q\omega/\sqrt{(r^2 - \omega^2)^2 + 4p^2\omega^2}]\sin(\omega t - \Phi + \Psi). \;\ldots\ldots\; (9)$$

From this equation it is obvious that the response is small for $\omega \cong 0$; that is for a long period, and also small for ω large or for short periods. The exact shape of the final response curve is governed by the constants k, μ, r, and p.

The following method was used to determine the constants. A sine wave generator capable of generating a wave with period continuously variable between about 2 seconds and 400 seconds was available.

A small permanent magnet was fastened to the beam of the seismograph and the current from the generator sent through a coil placed near the magnet. The force acting on the beam was assumed proportional to the voltage across the coil or in (4)

$$F = mE \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (10)$$

where E is maximum voltage during a cycle and m is a constant.

The motion of the beam was measured by a microscope and scale mounted directly over the beam. The generator was placed in operation and the amplitude of motion for various frequencies read in the microscope. These amplitudes were plotted against T, the period of the applied force, and k and μ for best fit of the data were determined. Figures 2 and 3 show these results for the E-W and N-S components respectively. The vertical scale has been arbitrarily reduced to amplitude 1.00 for an infinite period. From (3) the response of the beam R(ω) to Earth motion is computed and is also shown in Figures 2 and 3.

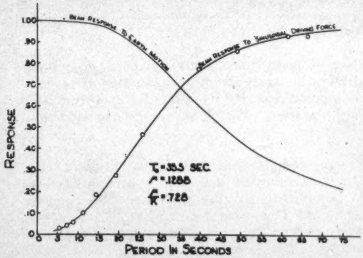

Fig. 2--Beam response curve E - W component

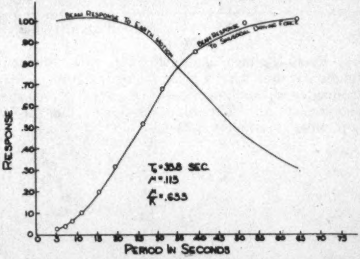

Fig. 3--Beam response curve N - S component

The angle θ, through which the mirror of the pick-up turns was not measured directly. A beam of light directed on this mirror is reflected to a split photocell, the output of the photocell is amplified and sent to the recording galvanometer. Figure 4 shows this circuit. If y denotes the deflection on the recording paper, then

$$y = B\theta \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\; (11)$$

where B is a constant depending on the intensity of light source illuminating the photocell, the amplification of the amplifier, and the setting of the galvanometer sensitivity control.

Simultaneously with the determination of the beam amplitude a record is run which gives the response y on the record for each frequency.

The ratio of the amplitude y on the record to Q, the amplitude of the beam is then

$$\text{amp } y/Q = Bq\omega/\sqrt{(r^2 - \omega^2)^2 + 4p^2\omega^2}$$

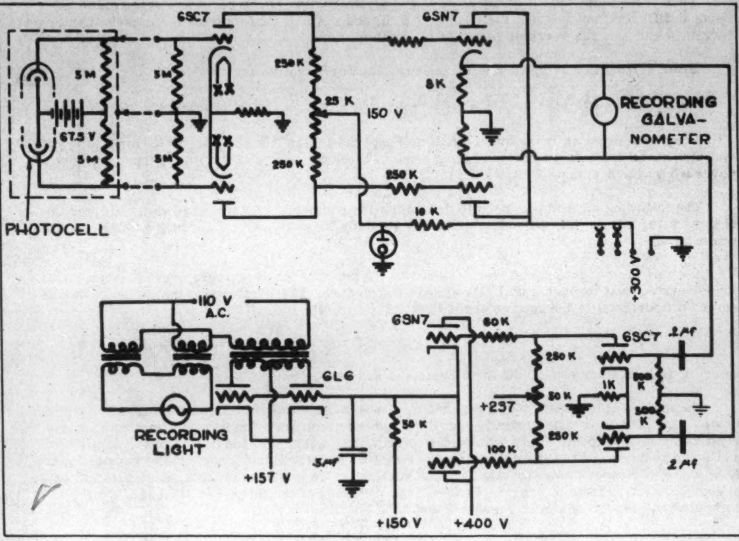
6SC7
6SN7
5M
5M
5M
5M
67.5 V
250 K
25 K
150 V
8K
RECORDING GALVANOMETER
250 K
250 K
10 K
+300 V
PHOTOCELL
110 V A.C.
6SN7
60 K
6SC7
.2 µf
250 K
1K
500 K
50 K
+237
500 K
250 K
100 K
2 µf
6L6
50 K
.5 µf
+157 V
RECORDING LIGHT
+150 V
+400 V

Fig. 4--Photocell amplifier and recording light control circuit

From the measurement of this ratio as a function of ω the quantities r, p, and Bq may be determined, thus determining the over-all magnification of the instrument as a function of ω the frequency of the disturbance. Figure 5 shows the computed magnification for the E - W and N - S components as a function of the period T of the Earth's motion. The phase angles are also easily computed as a function of T.

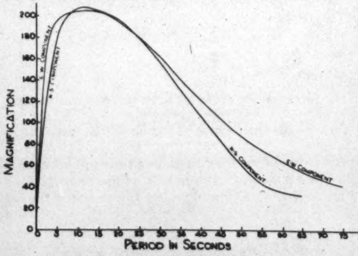

Fig. 5--Over-all magnification

In order to eliminate the variation of trace density with speed of motion, a circuit has been designed to control the intensity of the recording light. The present circuit is shown in the lower part of Figure 4. The output of the photocell amplifier is fed into a condenser-resistance network which effectively differentiates the signal; this derivative is amplified by a 6SC7 tube and then rectified by a 6SN7. The output of the 6SN7 controls a pair of 6L6's which load a power transformer, the primary of which is connected in series with the transformer supplying the recording light. The recording light is 6.3 volt 3.5 amp normal operation. The optical system is arranged so that a satisfactory zero trace is obtained with 2.8 volts on the light. With the circuit and amplifier shown, a motion of the beam of amplitude 0.004 inches and period 9.0 seconds places a voltage of 5.2 volts on the light and increases its intensity by a factor of eight during the instant of maximum motion. The light is of the straight filament type and has shown no apparent lag with applied periods down to three seconds.

Figure 6 is an unretouched reproduction of a record taken May 13-14 with this system in operation.

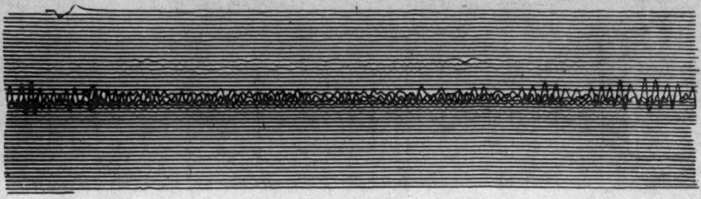

Fig. 6--E-W component, May 13, 1947

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ERRORS IN WIND-SPEED MEASUREMENT

Ronald L. Ives and Evelyn L. Kroona

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Abstract--This paper describes common errors that are often disregarded in the securing and application of wind-speed data, obtained by the use of the conventional rotating-cup anemometer. The magnitudes of the errors, as determined by computation and from extensive field tests in the Salt Lake Desert, are discussed, and their importance in various types of meteorological work is briefly considered. Some remedial measures are summarily outlined.

Introduction--Wind-speed measurements made during the early stages of a rather extensive program of air-motion studies disclosed a large number of apparent discrepancies between figures obtained with various methods and instruments, particularly when the duration of the test or measurement was short. Some, but not all, of these discrepancies cancelled out when the measuring period was increased. Material here presented is the result of 45 months of intensive field and laboratory research largely devoted to wind-speed measurements. Remedial measures have, in general, been tested in actual field operation for periods exceeding six months. Although perfection is neither claimed nor expected, results cited should be free from most of the errors and misconceptions inherent in short run tests.

Instrumental errors--The conventional rotating-cup anemometer, although probably the best all-around instrument now known for wind-speed measurement, has several inherent defects, chief among which is its unequal response to acceleration and deceleration of the wind. In a gusty wind, it will normally read high. This defect, and several others, have been thoroughly discussed by FERGUSSON [see "References" at end of paper, 1939]. Experiments during this study suggest that Fergusson was most fortunate in his choice of instruments, so that his results represent the best data that can be secured by use of cup anemometers rather than average station results.

Several other instrument deficiencies, including temperature coefficient, vibration, and contact resistance (mechanical), have been described by IVES [1947], and some remedial measures briefly discussed. The chief cause of instrumental error, however, appears to be lack of ordinary maintenance, rather than inherent design deficiencies. Although a Signal Corps type ML-80 anemometer will continue to operate after a fashion for as long as five years without any form of maintenance, its accuracy and dependability may decline quite rapidly if maintenance and cleaning instructions are not thoroughly and systematically followed.

Observational errors

Even with a perfect instrument, current methods of measuring wind speed by use of a contacting anemometer are subject to considerable error, because of disregarded fractions and the duration of contact closure. At very high wind speeds, the reaction time of the observer is an additional cause of error. This will not be considered here, because other errors of considerably greater magnitude completely overshadow the observer's personal error. Three common methods of measuring wind speed by use of a standard three-cup rotating anemometer (Signal Corps ML-80 or equivalent equipped with 1/60th-mile contacts) and a stopwatch will be considered here.

First method--When all equipment is ready for operation, timing is started. During one minute, all speed signals are counted. The number of speed signals received plus the instrument correction is the wind speed reported. Reference to Figure 1 shows that this method may be exactly correct as in A, or considerably in error as in B and C. If the sum of the initial and terminal fractions is equal to (1 - d), no observational error will be present. This, however, is true in only a few observations.

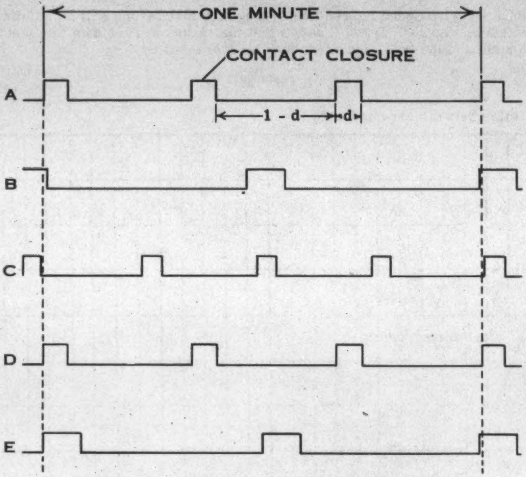

Fig. 1--Observational error chart with speed signals shown as they would be printed by a tape recorder

Limiting errors are shown in Figure 1, B and C. In B, three speed signals are received, but the sum of the time intervals is only slightly greater than (2 + d), and the true speed is slightly less than two mph. In C, three speed signals are likewise received, but the sum of the time intervals here is slightly less than (4 - d), so that the true speed is actually slightly less than four mph.

Reference to Figure 1 shows that the true wind speed determined by this method can be indicated by the formula

$$S = N \pm (1 - d) + C \quad \ldots\ldots (1)$$

in which S is true wind speed; N is indicated wind speed; 1 is one speed interval; d is duration of speed signal; and C is instrument correction.

Maximum per cent error inherent in this method, as computed from the formula

$$E = 100[(1 - d)/S] \quad \ldots\ldots (2)$$

in which E is the per cent error, and infinitesimals are omitted, is shown in Figure 2. In this computation, the error factor (1 - d) is arbitrarily evaluated at 0.9. The maximum error shown is the sum of the observational error and the instrument error, both being of the same sign. A partial cancellation of errors will occur when the two are of opposite sign.

Second method--Timing is started simultaneously with the beginning of the speed signal, and all perceived signals, including the first, during one timed minute, are counted. The reported wind speed is this figure plus the instrument correction. Some observers do not count the initial signal, and report the sum of all signals except the first, plus the instrument correction, as the wind speed. Justification for this, and several other variant procedures, is somewhat nebulous.

Reference to Figure 1, D and E, indicates that this method may produce an accurate speed figure (D), or may give a fictitiously high value (E). In D, three speed signals and three whole spaces are included in a count that gives three mph (correction not included). In E, however, although the count is still three, the actual interval covered is only a little more than two. Hence, this second method will give speed figures that average too high by one half mph (infinitesimals omitted). Inspection of Figure 1, D and E shows that the range of error with this method is from zero to one mph high, and the true wind speed may be expressed by

$$S = N \pm M \quad \text{(3)}$$

in which M is a value between zero and unity.

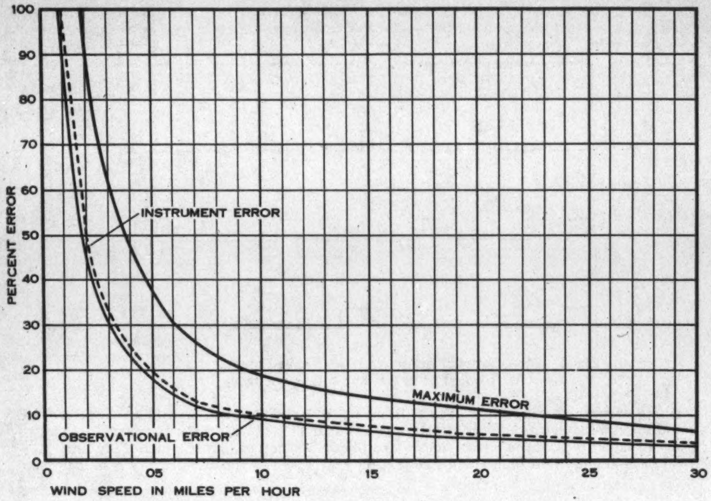

Fig. 2--Maximum error inherent in the first method of wind-speed timing; this is a point graph, so that values between ordinates are without meaning

Maximum observational error in per cent, computed from the formula

$$E = 100/N \quad \text{(4)}$$

is shown in Figure 3. The maximum value of this error is exactly equal to the commonly assumed instrument error, so that the two, if of opposite sign and equal magnitude, will cancel.

Third method--Timing is started immediately when the first signal is perceived, and is stopped immediately when the second speed signal is perceived. Sixty is divided by the stop-watch reading in seconds, the instrument correction is added, and the resulting figure reported as the wind speed. Alternately, the timing may be started as above and stopped at the eleventh speed signal (the initial signal is number one), and 600 divided by the stop-watch reading to obtain the uncorrected wind speed.

Computations may be eliminated by use of a special stop-watch dial [IVES, 1945 b and c], or the entire process may be performed automatically by use of an electric timer [IVES, 1945 a].

There are no first-order observational errors inherent in this method of wind-speed timing, because there are no disregarded fractions. Second-order errors, such as the observer's reaction time or the operational delay of the automatic timing device, are almost entirely compensating and with present equipment are negligible.

Summary of observational errors

The foregoing discussion indicates that so far as observational error alone is concerned the third method is by far the most accurate. The first method, although subject to definite observational

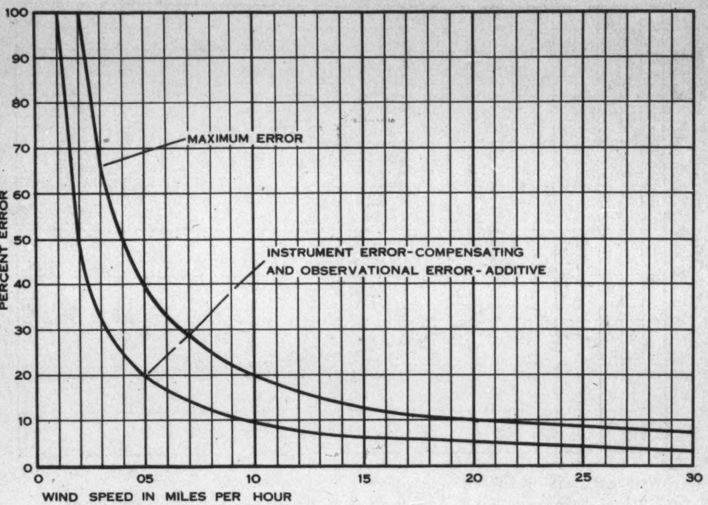

Fig. 3--Maximum error inherent in second method; values between ordinates are meaningless; observational error shown here is not compensating

errors, seems fairly accurate when a large number of observations are concerned, because the errors are compensating. The second method and its numerous minor variations is subject to a non-compensating error, and its use should be discontinued [IVES, 1946 b].

Sampling error

In many types of meteorological work it has been customary to represent the wind travel during a long period, such as an hour, by the speed measured during a short interval, such as one minute. This is an extrapolation of 60 to one.

The unsatisfactory nature of such an extrapolation being obvious, tests were begun in 1942 to determine the probable error resulting therefrom. The best basic data available in many instances were one-minute speed samples taken hourly. These tests, employing a battery of recording instruments at a number of locations in the Salt Lake Desert, were continued until late in 1945, when the results, consisting of 5000 or more hours of comparison observations of each extrapolation tested, were reduced.

Minute-to-hour extrapolations--The mean absolute sampling error produced by a 60-to-one extrapolation of the wind speed measured in one minute, as determined by comparing that speed with the total wind travel during the hour, is shown in Figure 4. Total travel was measured by means of an electric counter connected to the 1/60-mile contacts of the anemometer, and the one-minute sample was taken by Method 1. Results from a total of 20,000 hours of wind, measured at ten stations all in the same general area over a period of three years, are included in this computation.

With this large number of observations, plus and minus errors tend to compensate so that the total error was negligible. For this reason the curve of Figure 4 was computed from the absolute error (without regard to sign) according to the formula

$$E_T = (100/N)\Sigma\sqrt{[(T - S)/T]^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

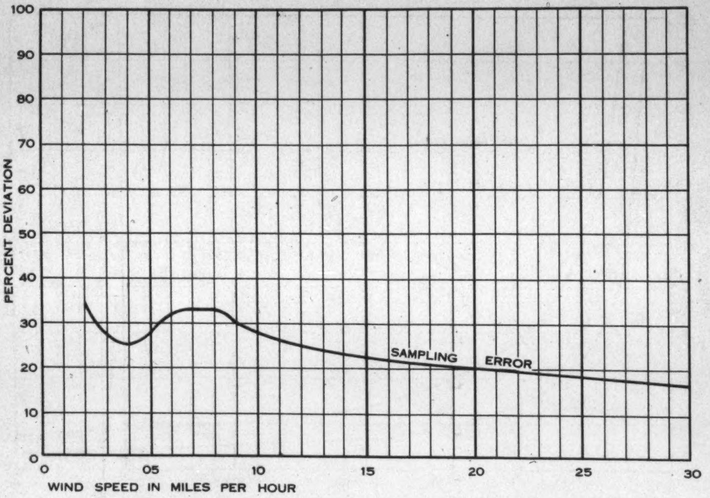

Fig. 4--Error produced by extrapolation of one minute's wind travel by a factor of 60; curve based on 20,000 hours of observations; cancellation of compensating portions of instrument and observational errors is assumed

in which E_T is mean absolute error of sampling in per cent for a given travel value T; N is number of observations at that travel value; T is travel, in miles, during the hour; and S is speed as determined by a one-minute sample. Because of the large number of samples, it is believed that the observational error is completely cancelled out. Instrument error is at least partially eliminated by the use of the same instrument for measuring both the total travel and the one-minute sample.

It should be emphasized that the cancellation of errors in a long sequence of observations does not enhance the accuracy of a single observation or insure the validity of a single extrapolation or small group of them.

Sixtieth-mile-to-one-minute extrapolations--To test the validity of Method 3 for use in short-term observations, several standard 1/60-mile anemometers were equipped with additional contacting devices, so that they indicated sixtieths of a mile of wind by the standard contactors, and very much smaller fractions of a mile by subsidiary contactors (photoelectric, capacitative, inductive) which did not impose an additional mechanical load on the instruments. Wind travel during one minute, as indicated by the auxiliary contactors, was compared with wind speed as found by Method 3. Results are shown in Figure 5, which is based on more than 5000 tests.

Values of the mean absolute error of sampling were determined here for individual points by use of equation (5), with T taken as the one-minute average speed and five as the speed determined by Method 3. In Figure 5 it will be noted that the error at any given wind speed is affected by the height of the anemometer above the terrain and the nature of the terrain. Curves A and B are based on tests in a desert area with sparse sage cover. Experiments show that elevation of the anemometer to ten meters above the ground does not change the shape of the curve, but reduces the sampling error at all values by about 30 per cent. An even greater reduction is produced when the ground surface is covered with smooth crusted snow; a reduction of about ten per cent occurs when the ground surface is covered with water. During periods of smooth laminar air flow (air drainage), as determined by smoke tests, the sampling error at the two-meter level is reduced almost 60 per cent.

Whenever a surface covering of snow, dust, or sand starts to move, and the transported material is carried near the anemometer level, sampling errors increase markedly, producing a

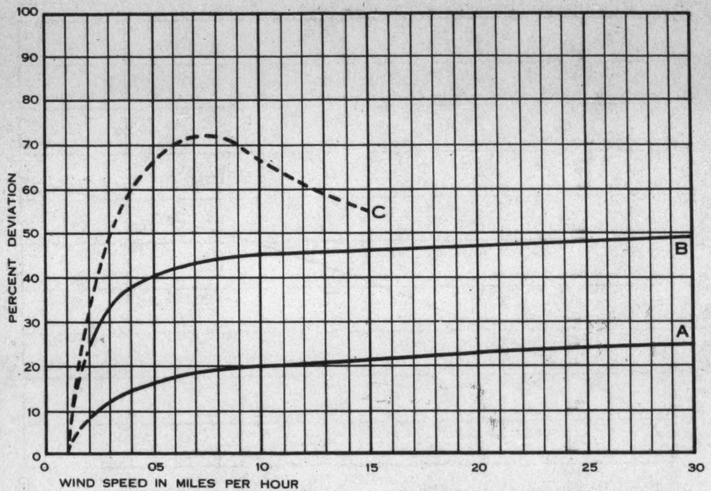

Fig. 5--Comparison of wind speeds determined by Method 3 and wind travel during one minute, for various conditions; curve A is based on 5000 observations with the anemometer at two meters above ground level; curve B is based on 3000 observations with the anemometer one meter above ground; curve C is based on 1200 observations in a sand dune area, with the anemometer about two meters above the average ground level

curve like C in Figure 5. As determined from tests so far conducted, the error increases until the air is carrying its maximum load for the speed and area, then decreases. In no instance did the amount of transported material even closely approach theoretical maximum; the observed maximum being approximately 70 per cent of the computed maximum.

The above data indicate that the error inherent in this extrapolation is a combined function of wind structure, wind load, anemometer height, and terrain type, so that no simple universal correction factor can be derived to bring the accuracy of this method into accord with other methods.

Sixtieth-mile-to-hour extrapolation--Using methods similar to those described above, the wind travel in one hour was compared to the extrapolated travel, based on Method 3 for slightly more than 5000 hours, using a photographic recorder in addition to chart recording instruments and manually operated stations. Results of these tests, computed by means of Equation (5), with S equal to the speed as determined by Method 3 are shown in Figure 6. In computing these values, all of the travel figures recorded during any hour in which the anemometer slowed below its practical operating limit (two mph) were discarded. This eliminated data from dust devils and squalls of short duration during periods of predominantly low wind speed. Slowages were indicated automatically in the photorecorder [IVES, 1946 a], and were detected in the instrument charts by use of a "no dice" gauge.

From the plotted data, it should be apparent that this method is undependable at low wind speeds and worthless at high, when air motion is normally turbulent. Some field tests indicate that when air flow during the entire period is laminar, error due to this extrapolation (which is 1800 to one at 30 mph) does not exceed 20 per cent.

Summary of sampling errors

Review of errors introduced by extrapolating a small sample to cover a relatively long period discloses that extrapolation of one minute's wind speed to determine the wind travel during the hour sampled introduces a sampling error that averages more than 30 per cent at most speeds

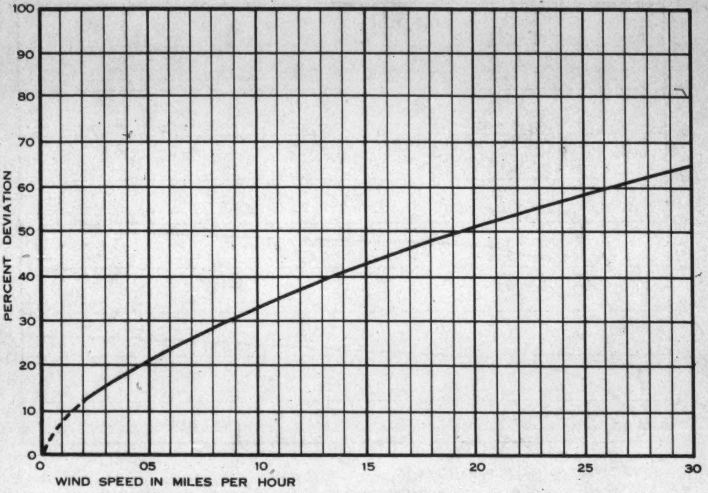

Fig. 6--Comparison of total wind travel during one hour with the travel figure obtained by extrapolating the wind speed as measured by Method 3

below ten mph; and that the error decreases with increased wind speed, declining to about 17 per cent at 30 mph.

When the third method of timing, which has no observational error, is used, the gain secured by eliminating the observational error is more than offset at most speeds by the great increase in sampling error resulting from the shorter time period for which the sample is taken. Hence, the value of the third method in most types of meteorological work is quite limited.

Eddy effects

Field tests, made with a "forest" of wind instruments, show that, particularly at low speeds, wind travel is not by any means a simple linear flow, but is a complex mass of whirling eddies whose average dimensions and rate of motion seem to be a direct but certainly not a simple function of wind speed.

Measurements made in the Targhee National Forest in 1943 by a joint field party of the National Defense Research Committee and the Chemical Warfare Service, suggest that eddies having diameters of 150 to 350 feet are common near the ground when average wind speeds approximate 0.75 mph and that the eddy diameter increases rapidly with wind speed until, at about eight mph, the eddy effects are much less pronounced.

A limited number of additional tests, conducted in absolutely barren and level areas in the Great Salt Lake Desert, gave slightly larger eddy diameters, with substantially identical behavior. When the eddies were loaded with smoke it was noted that those having diameters of less than 200 feet behaved as single solid entities, with the axis of rotation substantially vertical. The larger eddies had a more complex structure, somewhat resembling a nest of loosely-fitted rings gyrating about a somewhat indefinite center. Eddies were further complicated in some instances by the presence of small parasitic whirls.

When an anemometer is located in an eddy, the measured wind velocity will be the vector sum of eddy rotation and eddy translation. If it is assumed that the rotational component of the eddy is a definite function of the distance of the instrument from the center of the eddy, it is theoretically possible to compute the trajectory of the eddy and its rate of rotation from simultaneous readings on three or more anemometers.

Field tests indicate that such an assumption is doubtful, especially in the case of large eddies, and it appears that additional instruments rather than attempts at computation offer the best practical solution to eddy problems.

Summary of errors

The foregoing data and computations give a most disquieting picture of the present status of wind-speed measurements. Certainly, when a single measurement is critical, the amount that it may be in error is somewhat alarming. On the other hand, most of the errors are at least partially compensating, and for some purposes extrapolation is unnecessary so that in those cases the sampling error is unimportant.

Importance of errors--Although all of the errors listed, and some others, are of importance in theoretical meteorology, the various practical branches of the science have differing requirements as to precision, duration, and predictability. In aeronautical meteorology, the major need is for accurate wind data to be used within a very few minutes. For this reason, extrapolation error is unimportant, but instrumental, observational, and eddy errors, and variation of wind with height are important. In addition, means of getting the information to an incoming pilot more promptly are badly needed. With lighter-than-air equipment, the most critical problem at present seems to be prediction of the violence of eddies in the free air. Although such a study is beyond the scope of this paper, further investigation of surface eddies may produce data that will be useful in this problem. In synoptic work, present methods of wind measurement, at their best, seem nearly adequate. Future modifications of method to secure greater accuracy must be made in such a manner that the existing system of synoptic work is not halted or disrupted. The present weather-forecasting system, unlike a post exchange, cannot be shut down periodically for inventory and alterations.

It is in certain phases of applied meteorology, such as those dealing with smelter fumes, crop dusting, and smoke control, that the deficiencies of present methods are most serious. In this type of work, an accurate determination of resultant wind must be made, a procedure dependant for its final accuracy upon the accuracy of the basic data. The period covered by most determinations is relatively short--hours or days--so that the inherent errors do not usually compensate. It is in this field also that changes in instrumentation and procedure are most easily made, for most tests are of relatively small areal extent, and are not closely interrelated with others.

Reduction of errors

A part, and only a part, of the needed improvement in wind data can be brought about by improved instrumentation. Another fraction can be produced by adoption of better indicating and recording methods; a third part awaits the completion of long-continued painstaking local studies to determine the limitations of various methods under differing local conditions.

Instrumental error--Shortcomings of the rotating-cup anemometer are largely fundamental, constant, and predictable, and for the most part are relatively small. The chief remediable cause of error is poor maintenance. If the instruments are properly and systematically cared for, errors introduced by them are almost negligible, but if the anemometer is not properly maintained, no improvement in the auxiliary equipment or methods will appreciably increase the accuracy of reported wind data.

Where short-term wind-speed measurements on a constant time base are needed, the first method described above is the best in general use. Accuracy of this method, which is standard in many weather services, increases with wind speed, and may be further increased by use of a smaller contacting interval, such as 1/120th of a mile. The second method of wind-speed timing, with its numerous variations, should be abandoned completely. It is probably a war-born perversion of Method 1. The third method satisfactorily supplies the need for an accurate short-term wind-speed measurement on a constant distance base.

By use of a condenser-discharge indicator [MIDDLETON, 1941] or Grinnell Recorder [GRINNELL, 1945], error caused by disregarded fractions in Method 1 can be eliminated, provided an indication of the average wind speed during the last n seconds is satisfactory.

By applying the features of Method 3 to a time base of approximately one minute, a minimum-error short-term wind-speed measurement method, suited for either manual or automatic operation, has been worked out. This method, described elsewhere [IVES, 1946 c], eliminates the disregarded fractions which produce the error in Method 1.

The error resulting from extrapolation of a one-minute sample of wind speed to determine the wind travel during the hour sampled is almost entirely caused by wind structure, and hence cannot be eliminated by instrumental improvements. If, in place of the extrapolation, the total wind travel during the hour (a 100 per cent sample) is reported, the sampling error is completely eliminated. This can be done by hourly reading of the odometer attached to most anemometers, a most inconvenient and laborious procedure, or by use of an electric counter controlled by the anemometer contacts [IVES, forthcoming]. This arrangement can be modified by use of a submultiple contactor to indicate wind travel in miles and tenths, instead of sixtieths of a mile, or by use of a printing counter, to print the wind travel periodically on paper. The latter method has been in use by the United States Weather Bureau at its principal stations for many years.

Although a portion of extrapolation error, particularly at low wind speeds, is certainly caused by eddy effects, present knowledge does not permit any very definite statements regarding the magnitude of eddy error. Further study in this field is quite definitely needed. Eddy error may be reduced in short-period measurements by averaging the indications of a number of anemometers, distributed through the area concerned, and by extending the time base of the speed measurements.

Authorship and acknowledgments

This study was initiated under authorization of John R. Burns, Chemical Warfare Service; and carried on with the active cooperation of I. S. Taylor, Chemical Warfare Service. Project supervision, instrument design and construction, and the writing of this report are the work of the senior author, who takes full responsibility for statements therein. Training and supervision of WAC observing crews, care and organization of the records, much maintenance of field and station equipment, and many of the more difficult observations, are the work of the junior author. An appreciable part of the computation was done by WAC computing squads under the supervision of Rita K. Wilkinson, WAC. Installation and heavy maintenance work was done by crews under the supervision of Werner D. Schnackenburg and Robert A. Arnberg. WAC observers deserving of special mention for diligence beyond ordinary duty requirements include Dorothy Lankin, Stella C. Pieklo, Ruth Ells, Annette Freeman, and Agnes J. Mernin. The senior author is indebted to S. W. Grinnell, now at Stanford University, for many helpful discussions of wind-measurement problems; and to the junior author for voluntarily remaining on duty, when eligible for discharge, until an accumulation of research reports was completed.

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PRELIMINARY MEASUREMENTS OF SOLAR ENERGY RECEIVED ON VERTICAL SURFACES

I. F. Hand

Abstract--So far as the writer has been able to determine, some of the rather voluminous data here presented are the first of their kind ever obtained through continuous registration. In addition to values of solar and sky energy received on various surfaces, simple formulas have been evolved to enable the reader to calculate the amount of solar energy to be expected on vertical surfaces facing south. Auxiliary tables should facilitate the calculation of the angle of the Sun's rays on a south vertical surface at any hour and on any day at various latitudes.

The insistent demand for values of solar energy impinging upon other than horizontal surfaces or those normal to the sun prompted the United States Weather Bureau to initiate an additional program of observations at Blue Hill Observatory, Milton, Massachusetts, in March 1945. Two Eppley 180-degree pyrheliometers were exposed vertically to the south and east, respectively; another was exposed horizontally beneath an occulting ring. By occasional adjustment of the ring, the receiving surface of the pyrheliometer was continuously shaded from the direct rays of the sun; adjustment of the reduction factor compensated for the slight loss of sky radiation due to shading of an arc of the sky. The three new types of measurements, used in connection with regular normal-incidence measurements and values of total solar and sky radiation received on a horizontal surface, form the basis of these preliminary calculations.

Table 1 shows the weekly mean values of the three new types of measurements by hours, from March 26, 1945 to June 3, 1946, expressed as ratios of the three types to the total solar and sky radiation received on a horizontal surface for each day; except that diffuse radiation measurements began on October 29, 1945. Under the column headed "Daily total" are given weekly means of daily totals of solar radiation received on a horizontal surface. Ratios of hourly values during the hours which include sunrise and sunset have been omitted because of the difficulty of measuring radiation accurately at those times. H. Landsberg has plotted the ratios of the "Mean" column of Table 1: the smoothed curves are shown in Figure 1.

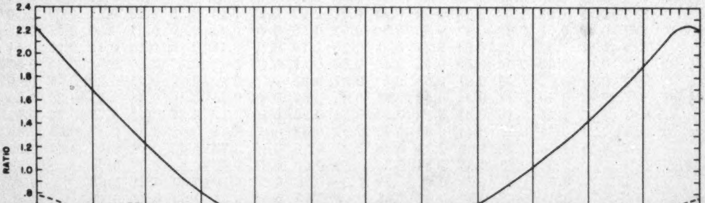

Fig. 1--Ratio of solar radiation falling on vertical surfaces, south (S) and east (E), to total radiation (T) on a horizontal surface

Where sufficient data on solar radiation at normal incidence are available, a fair estimate may be made of the amount of solar energy to be expected on cloudless days on a vertical surface facing south through the use of the formula

$$I_v = I_n (\cos a \cos D) + d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Table 1--Ratio of weekly means of radiation received hourly on vertical surfaces, facing south (S) and east (E) respectively, and diffuse radiation (D) on a horizontal surface to total radiation (T) received on a horizontal surface at Blue Hill, Massachusettes (Continued)

Week ending	Ratio	Time														Mean	Daily total[a]
		6	7	8	9	10	11	12	13	14	15	16	17	18	19		
1945																	$\frac{\mathrm{gm\ cal}}{\mathrm{cm^2}}$
Apr. 1	S/T	...	0.47	0.61	0.69	0.76	0.79	0.78	0.80	0.81	0.79	0.76	0.66	0.58	...	0.76	000
	E/T	...	4.41	2.47	1.56	1.13	0.70	0.34	0.18	0.21	0.20	0.19	0.22	0.31	...	0.63	
Apr. 8	S/T	...	0.43	0.50	0.63	0.68	0.72	0.71	0.71	0.72	0.75	0.69	0.61	0.47	...	0.68	
	E/T	...	4.34	2.25	1.50	1.02	0.62	0.31	0.25	0.28	0.26	0.24	0.26	0.29	...	0.65	339
Apr. 15	S/T	...	0.50	0.53	0.63	0.69	0.72	0.73	0.75	0.76	0.75	0.71	0.60	0.43	...	0.70	
	E/T	...	3.32	2.03	1.50	1.03	0.62	0.30	0.15	0.15	0.14	0.15	0.15	0.07	...	0.56	534
Apr. 22	S/T	...	0.41	0.41	0.57	0.65	0.82	0.82	0.79	0.80	0.66	0.62	0.50	0.32	...	0.69	
	E/T	...	3.65	2.13	1.43	1.00	0.74	0.45	0.31	0.31	0.29	0.22	0.17	0.09	...	0.70	400
Apr. 29	S/T	...	0.57	0.47	0.54	0.67	0.65	0.63	0.73	0.66	0.69	0.64	0.55	0.46	...	0.63	
	E/T	...	2.00	1.51	1.11	0.89	0.59	0.40	0.36	0.35	0.34	0.26	0.22	0.25	...	0.64	283
May 6	S/T	...	0.51	0.45	0.46	0.42	0.56	0.67	0.57	0.64	0.70	0.68	0.54	0.39	...	0.57	
	E/T	...	1.83	1.44	1.10	0.87	0.59	0.41	0.35	0.35	0.38	0.27	0.26	0.22	...	0.59	352
May 13	S/T	...	0.26	0.29	0.31	0.48	0.58	0.54	0.54	0.50	0.52	0.50	0.33	0.27	...	0.46	
	S/T	...	1.67	1.46	1.09	0.84	0.61	0.38	0.26	0.27	0.32	0.33	0.22	0.25	...	0.58	380
May 20	S/T	0.29	0.29	0.22	0.29	0.39	0.51	0.55	0.57	0.58	0.55	0.52	0.47	0.43	0.37	0.47	
	E/T	2.69	2.38	1.56	1.10	0.85	0.54	0.34	0.19	0.20	0.19	0.18	0.19	0.23	0.27	0.55	386
May 27	S/T	0.40	0.30	0.27	0.30	0.33	0.45	0.47	0.50	0.48	0.48	0.43	0.31	0.25	0.30	0.40	
	E/T	2.86	2.61	1.72	1.19	0.83	0.58	0.39	0.25	0.25	0.25	0.25	0.26	0.23	0.26	0.68	517
June 3	S/T	0.39	0.36	0.36	0.33	0.39	0.49	0.42	0.43	0.45	0.31	0.27	0.26	0.27	0.24	0.38	
	E/T	3.22	2.03	1.34	1.16	0.79	0.49	0.27	0.20	0.23	0.19	0.18	0.18	0.21	0.20	0.51	478
June 10	S/T	0.31	0.35	0.33	0.26	0.33	0.40	0.45	0.47	0.45	0.47	0.39	0.36	0.44	0.53	0.40	
	E/T	1.55	1.37	1.26	1.02	0.93	0.67	0.47	0.38	0.32	0.34	0.34	0.23	0.32	0.32	0.63	405
June 17	S/T	0.49	0.34	0.28	0.27	0.30	0.38	0.49	0.45	0.50	0.47	0.56	0.33	0.32	0.36	0.39	
	E/T	3.52	2.08	1.49	1.18	0.85	0.57	0.41	0.24	0.26	0.28	0.39	0.29	0.28	0.32	0.66	480
June 24	S/T	0.44	0.39	0.35	0.34	0.41	0.47	0.47	0.49	0.45	0.48	0.46	0.30	0.36	0.57	0.43	
	E/T	2.19	1.99	1.39	1.01	0.74	0.48	0.27	0.20	0.19	0.20	0.21	0.17	0.22	0.33	0.50	563
July 1	S/T	0.63	0.36	0.33	0.36	0.47	0.45	0.57	0.50	0.49	0.44	0.44	0.48	0.55	0.80	0.47	
	E/T	2.61	1.65	1.27	0.90	0.68	0.49	0.30	0.22	0.21	0.19	0.21	0.24	0.28	0.43	0.49	462
July 8	S/T	0.41	0.36	0.29	0.31	0.37	0.47	0.56	0.53	0.46	0.39	0.34	0.27	0.26	0.16	0.41	
	E/T	2.53	1.98	1.42	0.99	0.72	0.41	0.23	0.17	0.15	0.14	0.15	0.10	0.11	0.07	0.50	554
July 15	S/T	0.39	0.33	0.29	0.33	0.40	0.50	0.59	0.53	0.46	0.44	0.40	0.31	0.30	0.32	0.44	
	E/T	1.88	1.33	1.06	0.84	0.71	0.52	0.25	0.19	0.17	0.15	0.16	0.13	0.13	0.13	0.41	508
July 22	S/T	0.62	0.52	0.44	0.53	0.53	0.52	0.60	0.62	0.52	0.47	0.47	0.49	0.52	0.30	0.53	
	E/T	0.81	1.07	1.06	0.91	0.65	0.47	0.27	0.23	0.19	0.19	0.21	0.20	0.20	0.13	0.40	400
July 29	S/T	0.33	0.40	0.47	0.54	0.52	0.61	0.60	0.57	0.48	0.44	0.44	0.35	0.33	0.26	0.50	
	E/T	2.06	1.38	1.19	0.85	0.64	0.52	0.32	0.25	0.18	0.19	0.22	0.23	0.26	0.26	0.41	422
Aug. 5	S/T	0.21	0.32	0.32	0.41	0.48	0.53	0.57	0.58	0.57	0.51	0.46	0.34	0.32	0.43	0.49	
	E/T	3.15	2.16	1.38	1.10	0.79	0.48	0.26	0.20	0.19	0.20	0.24	0.24	0.25	0.32	0.52	533
Aug. 12	S/T	...	0.32	0.33	0.47	0.54	0.58	0.60	0.62	0.61	0.49	0.48	0.37	0.34	...	0.52	
	E/T	...	3.08	1.96	1.38	0.96	0.59	0.29	0.20	0.19	0.19	0.20	0.21	0.28	...	0.69	462
Aug. 19	S/T	...	0.45	0.43	0.52	0.61	0.65	0.66	0.65	0.62	0.62	0.53	0.43	0.41	...	0.58	
	E/T	...	3.18	2.24	1.52	1.04	0.70	0.38	0.26	0.21	0.22	0.24	0.28	0.37	...	0.68	542
Aug. 26	S/T	...	0.30	0.44	0.57	0.59	0.63	0.65	0.65	0.65	0.61	0.50	0.45	0.31	...	0.58	
	E/T	...	2.21	1.61	1.21	0.86	0.57	0.34	0.27	0.22	0.25	0.24	0.34	0.40	...	0.57	339
Sept. 2	S/T	...	0.44	0.53	0.66	0.73	0.75	0.76	0.76	0.51	0.72	0.71	0.59	0.61	...	0.71	
	E/T	...	2.36	1.69	1.24	0.82	0.58	0.33	0.21	0.20	0.19	0.23	0.26	0.39	...	0.53	369
Sept. 9	S/T	...	0.48	0.64	0.74	0.81	0.85	0.84	0.85	0.85	0.83	0.77	0.67	0.66	...	0.80	
	E/T	...	3.51	2.14	1.34	0.92	0.56	0.26	0.17	0.16	0.15	0.18	0.24	0.37	...	0.54	492
Sept. 16	S/T	...	0.73	0.80	0.78	0.81	0.82	0.89	0.83	0.89	0.78	0.77	0.83	0.78	...	0.82	
	E/T	...	2.11	1.64	1.07	0.83	0.57	0.36	0.24	0.22	0.22	0.21	0.28	0.40	...	0.49	323
Sept. 23	S/T	...	0.85	0.84	0.84	0.82	0.87	0.90	0.91	0.91	0.95	0.93	1.02	0.97	...	0.89	
	E/T	...	1.74	1.32	1.12	0.85	0.67	0.42	0.29	0.25	0.26	0.25	0.32	0.45	...	0.55	261
Sept. 30	S/T	...	...	1.14	0.97	1.03	0.92	0.97	1.09	1.06	1.05	1.21	1.22	...	...	1.04	
	E/T	...	...	2.59	1.34	1.03	0.62	0.33	0.29	0.27	0.27	0.28	0.36	...	...	0.60	256
Oct. 7	S/T	...	...	1.22	1.09	1.01	1.11	1.09	1.09	1.08	1.08	1.04	1.05	...	...	1.08	
	E/T	...	...	2.60	1.52	0.95	0.53	0.30	0.22	0.25	0.26	0.26	0.32	...	...	0.65	246
Oct. 14	S/T	...	...	1.24	1.36	1.26	1.10	1.12	1.11	1.18	1.30	1.40	1.44	...	...	1.22	
	E/T	...	...	2.58	1.82	1.14	0.65	0.31	0.21	0.26	0.23	0.24	0.32	...	...	0.66	256

Table 1--Ratio of weekly means of radiation received hourly on vertical surfaces, facing south (S) and east (E) respectively, and diffuse radiation (D) on a horizontal surface to total radiation (T) received on a horizontal surface at Blue Hill, Massachusettes (Continued)

Week ending	Ratio	Time														Mean	Daily total[a]
		6	7	8	9	10	11	12	13	14	15	16	17	18	19		
1945																	$\frac{\text{gm cal}}{\text{cm}^2}$
Oct. 21	S/T	...	...	1.75	1.47	1.40	1.38	1.36	1.37	1.42	1.45	1.63	1.99	...	...	1.44	328
	E/T	...	...	3.71	2.03	1.30	0.74	0.33	0.20	0.21	0.21	0.25	0.35	...	...	0.66	
Oct. 28	S/T	...	...	1.53	1.35	1.19	1.25	1.20	1.19	1.28	1.32	1.57	2.18	...	...	1.31	146
	E/T	...	...	3.30	1.86	1.12	0.58	0.36	0.28	0.29	0.28	0.28	0.31	...	...	0.66	
Nov. 4	S/T	...	...	...	1.29	1.21	1.44	1.52	1.45	1.57	1.61	1.50	...	...	...	1.48	200
	E/T	...	...	...	1.61	1.12	0.72	0.38	0.25	0.24	0.26	0.27	...	...	...	0.55	
	D/T	...	...	...	0.59	0.51	0.46	0.39	0.37	0.30	0.36	0.49	...	...	...	0.41	
Nov. 11	S/T	...	...	...	1.24	1.32	1.28	1.42	1.50	1.52	1.73	1.75	...	...	...	1.49	167
	E/T	...	...	...	1.44	1.12	0.68	0.38	0.26	0.26	0.24	0.26	...	...	...	0.50	
	D/T	...	...	...	0.70	0.56	0.51	0.48	0.35	0.36	0.35	0.45	...	...	...	0.44	
Nov. 18	S/T	...	...	...	0.38	0.74	0.71	0.81	1.25	1.35	1.56	1.99	...	...	...	1.18	94
	E/T	...	...	...	0.51	0.77	0.51	0.38	0.34	0.26	0.25	0.25	...	...	...	0.40	
	D/T	...	...	...	0.89	0.83	0.91	0.80	0.71	0.49	0.46	0.44	...	...	...	0.67	
Nov. 25	S/T	...	...	...	2.30	2.03	1.90	1.67	1.62	1.46	1.97	2.35	...	...	...	1.85	156
	E/T	...	...	...	2.54	1.51	0.88	0.41	0.26	0.25	0.26	0.27	...	...	...	0.70	
	D/T	...	...	...	0.39	0.31	0.24	0.35	0.37	0.31	0.42	0.54	...	...	...	0.35	
Dec. 2	S/T	...	...	...	1.91	1.57	1.45	1.42	1.57	1.61	1.80	2.17	...	...	...	1.63	113
	E/T	...	...	...	2.09	1.21	0.74	0.44	0.33	0.35	0.31	0.33	...	...	...	0.59	
	D/T	...	...	...	0.57	0.52	0.52	0.52	0.48	0.49	0.49	0.54	...	...	...	0.51	
Dec. 9	S/T	...	...	...	2.09	1.87	1.72	1.61	1.50	1.57	2.09	2.22	...	...	...	1.75	93
	E/T	...	...	...	2.17	1.37	0.82	0.48	0.36	0.37	0.34	0.38	...	...	...	0.71	
	D/T	...	...	...	0.65	0.55	0.50	0.51	0.55	0.57	0.50	0.68	...	...	...	0.54	
Dec. 16	S/T	...	...	...	2.51	1.99	1.88	1.88	1.78	1.91	2.45	3.09	...	...	...	2.07	146
	E/T	...	...	...	2.84	1.37	0.88	0.49	0.35	0.33	0.31	0.30	...	...	...	0.75	
	D/T	...	...	...	0.57	0.53	0.43	0.36	0.42	0.40	0.32	0.32	...	...	...	0.41	
Dec. 23	S/T	...	...	...	2.82	2.36	2.25	2.20	2.15	2.41	2.74	3.64	...	...	...	2.45	178
	E/T	...	...	...	3.04	1.77	1.07	0.53	0.35	0.35	0.34	0.37	...	...	...	0.76	
	D/T	...	...	...	0.49	0.36	0.26	0.20	0.22	0.19	0.21	0.24	...	...	...	0.24	
Dec. 31	S/T	...	...	...	1.65	1.78	1.69	1.62	1.76	2.01	2.06	2.84	...	...	...	1.87	116
	E/T	...	...	...	1.82	1.38	0.90	0.54	0.38	0.37	0.35	0.42	...	...	...	0.67	
(8-days)	D/T	...	...	...	0.56	0.56	0.46	0.49	0.54	0.53	0.49	0.47	...	...	...	0.51	
1946																	
Jan. 7	S/T	...	...	...	3.13	2.29	2.08	2.16	2.08	2.11	2.43	2.96	...	...	...	2.28	162
	E/T	...	...	...	3.29	1.66	0.95	0.53	0.32	0.33	0.32	0.38	...	...	...	0.81	
	D/T	...	...	...	0.42	0.37	0.31	0.27	0.25	0.31	0.30	0.36	...	...	...	0.31	
Jan. 14	S/T	...	...	...	2.49	2.09	1.99	1.81	1.90	1.90	1.95	2.53	...	...	...	2.01	152
	E/T	...	...	...	2.79	1.58	0.89	0.44	0.28	0.29	0.28	0.34	...	...	...	0.74	
	D/T	...	...	...	0.42	0.35	0.27	0.35	0.27	0.40	0.48	0.51	...	...	...	0.36	
Jan. 21	S/T	...	...	...	2.04	1.56	1.54	1.45	1.50	1.62	1.80	2.09	...	...	...	1.65	145
	E/T	...	...	...	2.32	1.28	0.80	0.47	0.33	0.32	0.32	0.38	...	...	...	0.66	
	D/T	...	...	...	0.62	0.60	0.56	0.54	0.50	0.46	0.46	0.58	...	...	...	0.53	
Jan. 28	S/T	...	...	...	1.77	1.54	1.47	1.52	1.57	1.48	1.73	1.88	...	...	...	1.60	184
	E/T	...	...	...	2.04	1.24	0.76	0.47	0.36	0.37	0.38	0.42	...	...	...	0.69	
	D/T	...	...	...	0.69	0.69	0.57	0.50	0.46	0.52	0.60	0.57	...	...	...	0.56	
Feb. 4	S/T	...	...	...	1.97	1.70	1.73	1.68	1.64	1.80	2.01	2.24	...	...	...	1.81	204
	E/T	...	...	...	2.39	1.45	0.83	0.39	0.27	0.27	0.26	0.25	...	...	...	0.69	
	D/T	...	...	...	0.43	0.34	0.25	0.21	0.32	0.30	0.28	0.30	...	...	...	0.29	
Feb. 11	S/T	...	...	2.04	1.69	1.65	1.59	1.46	1.51	1.53	1.59	1.82	1.93	...	...	1.60	217
	E/T	...	...	3.54	2.13	1.36	0.82	0.39	0.25	0.27	0.26	0.25	0.40	...	...	0.71	
	D/T	...	...	0.46	0.40	0.28	0.24	0.30	0.28	0.30	0.48	0.55	0.65	...	...	0.34	

Table 1--Ratio of weekly means of radiation received hourly on vertical surfaces, facing south (S) and east (E) respectively, and diffuse radiation (D) on a horizontal surface to total radiation (T) received on a horizontal surface at Blue Hill, Massachusettes (Concluded)

Week ending	Ratio	Time														Mean	Daily total[a]
		6	7	8	9	10	11	12	13	14	15	16	17	18	19		
1946																	$\frac{gm\ cal}{cm^2}$
Feb. 18	S/T	...	...	2.28	1.75	1.34	1.45	1.22	1.31	1.20	1.39	1.59	1.94	...	...	1.42	242
	E/T	...	...	4.62	2.28	1.18	0.80	0.40	0.30	0.27	0.26	0.25	0.35	...	...	0.75	
	D/T	...	...	0.31	0.36	0.40	0.42	0.48	0.45	0.34	0.31	0.31	0.47	...	...	0.39	
Feb. 25	S/T	...	...	1.79	1.53	1.41	1.29	1.26	1.27	1.31	1.40	1.49	2.00	...	...	1.38	276
	E/T	...	...	3.74	2.06	1.33	0.78	0.45	0.32	0.32	0.35	0.35	0.47	...	...	0.72	
	D/T	...	...	0.28	0.24	0.22	0.22	0.23	0.25	0.27	0.31	0.31	0.39	...	...	0.26	
Mar. 4	S/T	...	...	1.59	1.25	1.20	0.97	1.19	1.17	1.21	1.27	1.35	1.66	...	...	1.22	255
	E/T	...	...	3.71	1.80	1.14	0.69	0.42	0.32	0.32	0.30	0.32	0.44	...	...	0.75	
	D/T	...	...	0.62	0.49	0.42	0.38	0.35	0.36	0.40	0.42	0.48	0.57		...	0.41	
Mar. 11	S/T	...	...	1.03	1.07	1.12	1.14	1.17	1.09	1.09	1.13	1.18	1.41	...	...	1.13	
	E/T	...	...	2.49	1.59	1.13	0.65	0.35	0.26	0.28	0.26	0.22	0.29	...	...	0.62	
	D/T	...	...	0.50	0.45	0.39	0.37	0.40	0.45	0.53	0.53	0.46	0.50	...	...	0.45	
Mar. 18	S/T	...	...	0.93	1.00	1.02	1.06	1.07	1.12	1.19	1.24	1.30	1.42	...	...	1.13	372
	E/T	...	...	2.25	1.62	1.05	0.64	1.32	0.20	0.20	0.20	0.22	0.29	...	...	0.59	
	D/T	...	...	0.46	0.31	0.24	0.23	0.22	0.23	0.25	0.30	0.33	0.41	...	...	0.27	
Mar. 25	S/T	...	...	0.75	0.80	0.89	0.94	0.96	0.99	1.00	1.05	1.11	1.16	1.28	...	0.97	452
	E/T	...	...	2.52	1.50	1.03	0.61	0.28	0.17	0.18	0.18	0.19	0.25	0.44	...	0.63	
	D/T	...	...	0.26	0.21	0.17	0.15	0.15	0.16	0.16	0.17	0.22	0.30	0.48	...	0.19	
Apr. 1	S/T	...	0.57	0.61	0.72	0.77	0.78	0.83	0.88	0.88	0.89	0.90	0.87	0.95	...	0.82	476
	E/T	...	3.91	2.33	1.41	0.94	0.61	0.32	0.20	0.20	0.21	0.26	0.31	0.42	...	0.64	
	D/T	...	0.39	0.27	0.28	0.34	0.31	0.23	0.25	0.25	0.35	0.44	0.50	0.53	...	0.31	
Apr. 8	S/T	...	0.50	0.51	0.62	0.65	0.71	0.80	0.73	0.79	0.80	0.82	0.85	0.98	...	0.73	317
	E/T	...	3.69	1.94	1.31	0.84	0.64	0.37	0.32	0.33	0.31	0.30	0.35	0.51	...	0.70	
	D/T	...	0.42	0.37	0.41	0.38	0.49	0.59	0.64	0.71	0.73	0.69	0.81	0.84	...	0.58	
Apr. 15	S/T	...	0.59	0.51	0.60	0.59	0.63	0.72	0.71	0.71	0.76	0.73	0.71	0.69	...	0.68	351
	E/T	...	3.31	1.89	1.33	0.91	0.61	0.33	0.26	0.28	0.32	0.30	0.27	0.33	...	0.65	
	D/T	...	0.55	0.41	0.39	0.53	0.58	0.62	0.53	0.68	0.73	0.72	0.73	0.79	...	0.60	
Apr. 22	S/T	...	0.39	0.34	0.48	0.58	0.64	0.68	0.68	0.71	0.72	0.70	0.64	0.58	...	0.63	559
	E/T	...	3.41	2.00	1.28	0.89	0.57	0.25	0.15	0.17	0.18	0.18	0.21	0.30	...	0.59	
	D/T	...	0.30	0.24	0.28	0.31	0.21	0.15	0.17	0.22	0.32	0.27	0.31	0.39	...	0.25	
Apr. 29	S/T	...	0.49	0.43	0.50	0.56	0.59	0.61	0.61	0.66	0.65	0.62	0.59	0.51	...	0.60	289
	E/T	...	2.17	1.34	0.91	0.74	0.56	0.38	0.27	0.23	0.23	0.22	0.24	0.26	...	0.51	
	D/T	...	0.64	0.55	0.64	0.58	0.54	0.63	0.56	0.45	0.51	0.47	0.55	0.58	...	0.55	
May 6	S/T	...	0.38	0.30	0.39	0.49	0.53	0.59	0.61	0.59	0.61	0.55	0.54	0.48	...	0.53	522
	E/T	...	2.51	1.70	1.15	0.80	0.55	0.28	0.19	0.18	0.17	0.21	0.22	0.25	...	0.57	
	D/T	...	0.37	0.28	0.27	0.26	0.30	0.31	0.29	0.30	0.31	0.32	0.35	0.38	...	0.31	
May 13	S/T	0.56	0.38	0.30	0.33	0.49	0.52	0.50	0.62	0.66	0.50	0.66	0.43	0.35	0.56	0.50	394
	E/T	2.37	1.75	1.47	1.00	0.73	0.55	0.30	0.29	0.25	0.24	0.32	0.23	0.19	0.31	0.57	
	D/T	0.56	0.50	0.38	0.36	0.34	0.39	0.39	0.53	0.53	0.45	0.49	0.57	0.56	0.62	0.44	
May 20	S/T	0.62	0.47	0.40	0.43	0.47	0.49	0.55	0.55	0.57	0.52	0.52	0.50	0.62	0.59	0.51	332
	E/T	1.50	1.32	1.05	0.77	0.58	0.49	0.35	0.28	0.26	0.29	0.37	0.28	0.28	0.34	0.47	
	D/T	0.88	0.76	0.70	0.67	0.79	0.72	0.60	0.63	0.58	0.63	0.71	0.72	0.83	0.83	0.68	
May 27	S/T	0.56	0.37	0.29	0.33	0.42	0.46	0.51	0.58	0.54	0.53	0.48	0.39	0.39	0.60	0.47	509
	E/T	2.97	2.06	1.51	1.06	0.77	0.51	0.28	0.19	0.18	0.16	0.20	0.22	0.26	0.40	0.55	
	D/T	0.56	0.41	0.31	0.27	0.23	0.30	0.31	0.32	0.31	0.29	0.31	0.37	0.37	0.48	0.31	
June 3	S/T	0.53	0.42	0.36	0.35	0.39	0.44	0.46	0.48	0.47	0.47	0.48	0.48	0.44	0.65	0.45	381
	E/T	2.71	1.80	1.26	0.92	0.73	0.51	0.29	0.25	0.23	0.23	0.24	0.23	0.22	0.29	0.52	
	D/T	0.57	0.49	0.49	0.47	0.37	0.38	0.36	0.41	0.40	0.44	0.53	0.53	0.56	0.61	0.43	

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[a] Mean daily total radiation received on a horizontal surface

Table 2--Values of cos a cos D for various declinations

North latitude	Declination											
	0°		-5°		-10°		-15°		-20°		-23°27′	
	Time[a]	Value	Time[a]	Value	Time[a]	Value	Time[a]	Value	Time[a]	Value	Time[a]	Value
	h m		h m		h m		h m		h m		h m	
30°	6 00	0.000	6 12	0.101	6 23	0.200	6 36	0.299	6 49	0.395	6 58	0.460
	7 00	0.129	7 00	0.205	7 00	0.278	7 00	0.349	7 00	0.417	7 00	0.463
	8 00	0.250	8 00	0.325	8 00	0.397	8 00	0.466	8 00	0.531	8 00	0.573
	9 00	0.354	9 00	0.428	9 00	0.499	9 00	0.566	9 00	0.628	9 00	0.669
	10 00	0.433	10 00	0.507	10 00	0.577	10 00	0.642	10 00	0.703	10 00	0.742
	11 00	0.483	11 00	0.557	11 00	0.626	11 00	0.691	110 00	0.750	11 00	0.789
	noon	0.500	noon	0.574	noon	0.643	noon	0.707	noon	0.766	noon	0.803
32°	6 00	0.000	6 13	0.103	6 25	0.205	6 39	0.305	6 53	0.403	...	...
	7 00	0.137	7 00	0.212	7 00	0.282	7 00	0.352	7 00	0.418	7 00	0.469
	8 00	0.266	8 00	0.338	8 00	0.408	8 00	0.475	8 00	0.538	8 00	0.580
	9 00	0.375	9 00	0.447	9 00	0.517	9 00	0.581	9 00	0.641	9 00	0.681
	10 00	0.459	10 00	0.531	10 00	0.598	10 00	0.662	10 00	0.721	10 00	0.758
	11 00	0.511	11 00	0.584	11 00	0.652	11 00	0.714	11 00	0.770	11 00	0.808
	noon	0.530	noon	0.602	noon	0.669	noon	0.730	noon	0.787	noon	0.822
34°	6 00	0.000	6 14	0.105	6 27	0.210	6 42	0.312	6 57	0.413	...	...
	7 00	0.144	7 00	0.217	7 00	0.286	7 00	0.354	7 00	0.419	7 08	0.479
	8 00	0.278	8 00	0.351	8 00	0.420	8 00	0.484	8 00	0.546	8 00	0.587
	9 00	0.396	9 00	0.465	9 00	0.533	9 00	0.597	9 00	0.654	9 00	0.693
	10 00	0.484	10 00	0.555	10 00	0.620	10 00	0.682	10 00	0.738	10 00	0.774
	11 00	0.540	11 00	0.610	11 00	0.679	11 00	0.736	11 00	0.790	11 00	0.826
	noon	0.559	noon	0.630	noon	0.695	noon	0.754	noon	0.809	noon	0.842
36°	6 00	0.000	6 15	0.108	6 29	0.215	6 45	0.320	...	...	...	...
	7 00	0.151	7 00	0.221	7 00	0.290	7 00	...	7 01	0.423	7 14	0.493
	8 00	0.293	8 00	0.363	8 00	0.430	8 00	0.493	8 00	0.553	8 00	0.592
	9 00	0.416	9 00	0.484	9 00	0.550	9 00	0.610	9 00	0.667	9 00	0.705
	10 00	0.509	10 00	0.577	10 00	0.641	10 00	0.701	10 00	0.755	10 00	0.789
	11 00	0.567	11 00	0.636	11 00	0.698	11 00	0.757	11 00	0.810	11 00	0.843
	noon	0.588	noon	0.656	noon	0.719	noon	0.776	noon	0.829	noon	0.861
38°	6 00	0.000	6 16	0.111	6 32	0.221	6 48	0.328	...	...	...	...
	7 00	0.158	7 00	0.227	7 00	0.293	7 00	...	7 06	0.434	7 19	0.505
	8 00	0.306	8 00	0.375	8 00	0.440	8 00	0.501	8 00	0.558	8 00	0.596
	9 00	0.436	9 00	0.502	9 00	0.565	9 00	0.623	9 00	0.678	9 00	0.714
	10 00	0.534	10 00	0.599	10 00	0.661	10 00	0.719	10 00	0.769	10 00	0.801
	11 00	0.594	11 00	0.660	11 00	0.722	11 00	0.778	11 00	0.828	11 00	0.859
	noon	0.616	noon	0.681	noon	0.743	noon	0.795	noon	0.847	noon	0.877
40°	6 00	0.000	6 17	0.114	6 34	0.226	6 52	0.338	...	...	...	...
	7 00	0.167	7 00	0.232	7 00	0.297	7 00	0.356	7 11	0.446	7 35	0.519
	8 00	0.321	8 00	0.387	8 00	0.450	8 00	0.509	8 00	0.564	8 00	0.600
	9 00	0.455	9 00	0.520	9 00	0.581	9 00	0.636	9 00	0.689	9 00	0.722
	10 00	0.557	10 00	0.621	10 00	0.681	10 00	0.736	10 00	0.785	10 00	0.816
	11 00	0.621	11 00	0.685	11 00	0.745	11 00	0.798	11 00	0.846	11 00	0.875
	noon	0.643	noon	0.707	noon	0.766	noon	0.815	noon	0.866	noon	0.895
42°	6 00	0.000	6 18	0.117	6 37	0.234	6 56	0.348	...	...	...	...
	7 00	0.174	7 00	0.237	7 00	0.300	7 00	0.359	7 17	0.460	7 32	0.535
	8 00	0.334	8 00	0.398	8 00	0.459	8 00	0.515	8 00	0.568	8 00	0.602
	9 00	0.473	9 00	0.536	9 00	0.595	9 00	0.649	9 00	0.699	9 00	0.729
	10 00	0.579	10 00	0.639	10 00	0.700	10 00	0.752	10 00	0.799	10 00	0.827
	11 00	0.646	11 00	0.709	11 00	0.766	11 00	0.817	11 00	0.862	11 00	0.889
	noon	0.669	noon	0.731	noon	0.788	noon	0.839	noon	0.883	noon	0.910

Table 2--Values of cos a cos D for various declinations (Concluded)

North latitude	Declination											
	0°		-5°		-10°		-15°		-20°		-23°27′	
	Time[a]	Value	Time[a]	Value	Time[a]	Value	Time[a]	Value	Time[a]	Value	Time[a]	Value
	h m		h m		h m		h m		h m		h m	
44°	6 00	0.000	6 19	0.121	6 39	0.241	...	...	...	...	...	...
	7 00	0.179	7 00	0.241	7 00	0.302	7 00	0.360	7 22	0.475	7 39	0.553
	8 00	0.346	8 00	0.409	8 00	0.467	8 00	0.521	8 00	0.572	8 00	0.606
	9 00	0.491	9 00	0.552	9 00	0.608	9 00	0.660	9 00	0.708	9 00	0.736
	10 00	0.602	10 00	0.661	10 00	0.717	10 00	0.767	10 00	0.811	10 00	0.838
	11 00	0.671	11 00	0.731	11 00	0.786	11 00	0.834	11 00	0.875	11 00	0.903
	noon	0.695	noon	0.754	noon	0.809	noon	0.857	noon	0.898	noon	0.923
46°	6 00	0.000	6 21	0.125	6 42	0.250	...	...	...	...	...	...
	7 00	0.186	7 00	0.246	7 00	0.303	7 00	0.373	7 29	0.492	7 46	0.570
	8 00	0.360	8 00	0.419	8 00	0.475	8 00	0.526	8 00	0.575	8 00	0.609
	9 00	0.509	9 00	0.567	9 00	0.621	9 00	0.672	9 00	0.715	9 00	0.743
	10 00	0.622	10 00	0.681	10 00	0.734	10 00	0.781	10 00	0.823	10 00	0.848
	11 00	0.694	11 00	0.752	11 00	0.804	11 00	0.851	11 00	0.888	11 00	0.915
	noon	0.719	noon	0.777	noon	0.828	noon	0.874	noon	0.913	noon	0.936
48°	6 00	0.000	6 22	0.130	6 45	0.259	...	...	...	...	...	...
	7 00	0.192	7 00	0.250	7 00	0.305	7 09	0.387	7 35	0.511	7 56	0.591
	8 00	0.372	8 00	0.428	8 00	0.481	8 00	0.531	8 00	0.577	8 00	0.610
	9 00	0.526	9 00	0.581	9 00	0.633	9 00	0.681	9 00	0.722	9 00	0.747
	10 00	0.642	10 00	0.699	10 00	0.749	10 00	0.794	10 00	0.836	10 00	0.856
	11 00	0.717	11 00	0.773	11 00	0.822	11 00	0.865	11 00	0.903	11 00	0.925
	noon	0.743	noon	0.798	noon	0.846	noon	0.890	noon	0.926	noon	0.947
50°	6 00	0.000	6 24	0.136	6 49	0.270	...	...	...	...	...	...
	7 00	0.198	7 00	0.254	7 00	0.307	7 14	0.403	7 53	0.532	...	...
	8 00	0.383	8 00	0.438	8 00	0.489	8 00	0.536	8 00	0.579	8 05	0.616
	9 00	0.542	9 00	0.595	9 00	0.645	9 00	0.689	9 00	0.729	9 00	0.753
	10 00	0.663	10 00	0.717	10 00	0.765	10 00	0.807	10 00	0.849	10 00	0.864
	11 00	0.740	11 00	0.793	11 00	0.840	11 00	0.881	11 00	0.917	11 00	0.935
	noon	0.766	noon	0.819	noon	0.866	noon	0.906	noon	0.940	noon	0.959

[a] Afternoon times measured from noon may be obtained by subtracting indicated morning times from 12

where I_v is the solar energy received on a vertical surface facing south; I_n, the solar radiation at normal incidence; a, the solar altitude; D, the difference in azimuth between the position of the sun and south; and d, the component of the diffuse energy from the sky and ground on a vertical surface facing south.

Values of I_n are available for solar radiation stations at Washington, D. C.; Madison, Wisconsin; Santa Fe and Albuquerque, New Mexico; Boston and Milton, Massachusetts; and Lincoln, Nebraska. A few similar data are available in records of the Smithsonian Institution for Burro Mountain, New Mexico; and Table Mountain, California. Values of a and D will be found in standard "altitude tables" [United States Hydrographic Office, Publication No. 214, Tables of Computed Altitude and Azimuth]. The variable d may be calculated by subtracting values obtained by use of the formula

$$I_v = (I_n \cos a \cos D) \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

from actual measured values obtained at the point of observation. Table 2 shows the basic values for cos a cos D for every hour from solar noon until sunrise or sunset for all latitudes from 30° to 50° N latitude, inclusive (in two-degree steps), and for solar declinations from 0° to -23°27′.

Figures 2 and 3 show the method of plotting I_n cos a cos D for declinations +23°27′ and -23°27′ at Blue Hill, Massachusetts. Similar graphs can be made for declinations ± 20°, ± 15°, ± 10°, ± 5°, and 0. Integration of the curves gives values for one-half day; doubling the values gives daily totals. These daily values can then be plotted on the dates corresponding to the chosen

Table 3--Relation of cloudiness to the ratios of radiation received on vertical surfaces facing east (E) and south (S), and of diffuse radiation (D), to the total solar and sky radiation (T) received on a horizontal surface

Month	Limits of cloudiness[a]	Average cloudiness for day	Ratio			Average cloudiness morning	Ratio		Average cloudiness afternoon	Ratio		
			E/T	S/T	D/T		E_{am}/T	D_{am}/T		E_{pm}/T	D_{pm}/T	E_{pm}/D_{pm}
1945												
Nov.	0.0 - 3.0	1.2	0.70	1.96	0.21	1.2	1.20	0.21	0.8	0.24	0.25	0.95
	3.1 - 7.0	5.0	0.54	1.59	0.43	5.2	0.94	0.38	5.0	0.24	0.38	0.65
	7.1 - 10.0	9.3	0.45	0.97	0.78	9.4	0.57	0.87	9.6	0.33	0.75	0.44
Dec.	0.0 - 3.0	1.4	0.78	2.46	0.22	1.1	1.33	0.21	1.0	0.32	0.21	1.52[b]
	3.1 - 7.0	5.9	0.63	1.66	0.59	4.9	0.92	0.47	5.4	0.42	0.65	0.65
	7.1 - 10.0	10.0	0.52	0.86	1.00	9.6	0.58	0.97	9.8	0.47	0.95	0.50
1946												
Jan.	0.0 - 3.0	1.3	0.79	2.29	0.22	1.2	1.31	0.21	0.7	0.30	0.21	1.39[b]
	3.1 - 7.0	5.8	0.65	1.50	0.56	5.2	0.96	0.55	5.3	0.34	0.52	0.65
	7.1 - 10.0	9.3	0.57	0.89	0.97	9.4	0.66	0.92	9.3	0.44	0.93	0.47
Feb.	0.0 - 3.0	1.2	0.72	1.68	0.17	1.3	1.19	0.16	1.0	0.25	0.17	1.45[b]
	3.1 - 7.0	4.6	0.81	1.57	0.45	4.2	1.23	0.40	5.3	0.34	0.55	0.61
	7.1 - 10.0	9.6	0.71	0.93	0.95	9.6	0.86	0.92	9.6	0.54	0.98	0.55
Mar.	0.0 - 3.0	0.8	0.65	1.07	0.17	0.8	1.11	0.16	0.7	0.19	0.18	1.04[b]
	3.1 - 7.0	5.7	0.59	1.00	0.40	4.8	0.90	0.33	5.2	0.24	0.38	0.64
	7.1 - 10.0	8.7	0.54	0.88	0.73	8.8	0.74	0.75	9.6	0.34	0.67	0.50

[a] Tenths of cloudiness: 0.0 - 3.0, clear; 3.1 - 7.0, partly cloudy; 7.1 - 10.0, cloudy. [b] Relatively large E_{pm} values caused partly by reflection of snow-covered terrain. Note: Subscripts am and pm indicate morning and afternoon values respectively.

declinations, and finally, by interpolation, one can obtain the annual march of direct solar radiation received on a vertical surface for any given location.

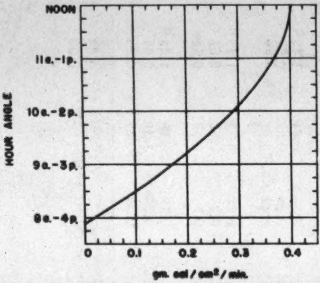

Fig. 2--Values of I_n cos a cos D vs. hour angle at Blue Hill, Massachusetts, with solar declination of +23°27′

Table 3 shows ratios of radiation received on vertical surfaces facing south and east and of diffuse radiation, to total solar and sky radiation on a horizontal surface. Values are broken down into three classifications of cloudiness... clear, partly cloudy, and cloudy skies... signified by the headings (in tenths of cloudiness) 0.0 - 3.0, 3.1 - 7.0, and 7.1 - 10.0, respectively. The average monthly cloudiness present, falling within each classification, is shown beneath the radiation ratio for that classification. The high ratios of afternoon values of radiation on an east surface to diffuse radiation for the November-to-March period, with clear skies, were due largely to the high reflective power of the snow, which covered the ground on nearly all of the days included in these four groups.

The United States Weather Bureau is now making correlation studies using data on percentage of sunshine, since it is believed that these will prove more accurate than cloudiness data. The first break-down will be in twelve divisions from 0 to 100 per cent sunshine, with ten intermediate divisions. First trials indicate that the 100 per cent sunshine group shows excellent results, but results obtained with partly cloudy skies demonstrate that considerably more data will be required before the other correlations can be considered dependable.

Preliminary conclusions include the following: (1) A south vertical surface receives more radiation than an east vertical surface, but east windows require considerable shading on summer mornings. (2) Direct measurements of solar energy impinging upon vertical surfaces are much more desirable than are calculations because of large variations in diffuse radiation with varying cloudiness.

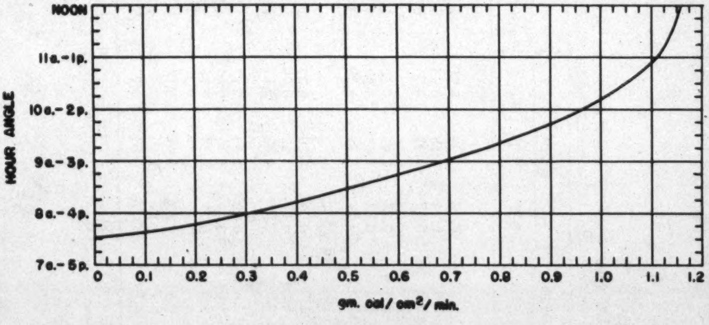

Fig. 3--Values of I_n cos a cos D vs. hour angle at Blue Hill, Massachusetts, with solar declination of -23°27′

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Milton, Massachusetts

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A SUMMARY OF THE USES OF RADAR IN METEOROLOGY

E. Dillon Smith and Robert D. Fletcher

Abstract

The use of radar to measure rainfall quantitatively was proposed. A hypothetical radar installation on Santiago Peak, California, was examined as a tool for determination of rainfall intensities over the whole of the Los Angeles coastal drainage basin. It was stressed that research should be undertaken that would be aimed toward a correlation between the image of an A-oscilloscope or a PPI-scope and the corresponding isohyetal pattern derived from observed rainfall data. A new table classifying precipitation intensity relative to average drop size, drop distribution, terminal speed of fall, and liquid water content of the air was presented (see Table 1).

Table 1--Precipitation values

Descriptive name	Precipitation intensity		Median rate		Median drop diameter	Terminal velocity of fall		Mass of liquid water	Number of drops per cu m
	From	To							
	in/hr	in/hr	in/hr	cm/hr	mm	ft/sec	m/sec	gm/cu m	
Fog	...	0.004	$2.5/10^5$	$6.3/10^5$	0.012	0.014	0.0044	0.040	443,000
Drizzle	0.004	0.03	0.008	0.020	0.6	8.3	2.5	0.022	195
Light rain	0.03	0.10	0.058	0.15	1.2	15.0	4.6	0.091	1010
Moderate rain	0.10	0.30	0.18	0.46	1.5	17.6	5.4	0.24	1370
Heavy rain	0.30	1.0	0.59	1.5	1.9	20.4	6.2	0.67	1870
Excessive rain	1.0	3.0	1.9	4.8	2.4	23.0	7.0	1.9	2650
Very excessive	3.0	...	6.1	15.2	3.0	25.6	7.8	5.6	3970
....	...	...	13.3	33.8	3.5	27.1	8.3	11.4	5120
....	...	...	26.0	66.0	4.0	28.2	8.6	21.3	6350

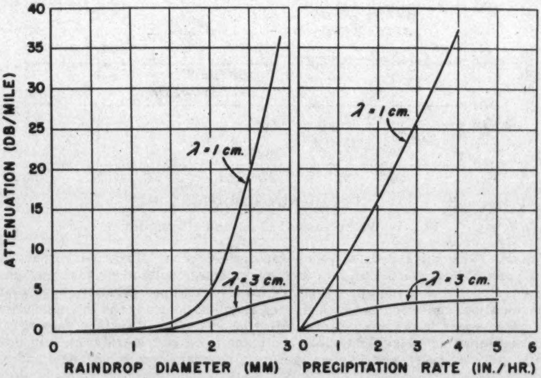
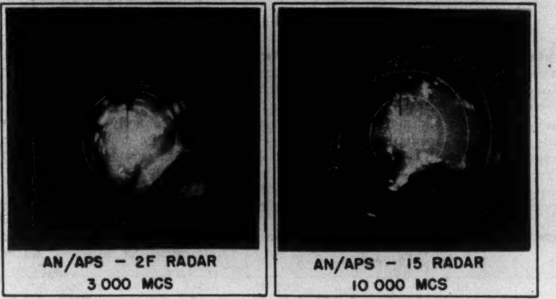


Fig. 1--Attenuation of 1 and 3 cm microwave one-way C. W. transmissions due to raindrop size and precipitation rate

The effects of water droplets on microwave attenuation in terms of decibels (db) per mile were illustrated and comparisons were made between 1 cm (30,000 megacycles per second) and 3 cm (10,000 mc) radar equipment (see Fig. 1). It was concluded that the return on a radar scope is a measure of the rainfall intensity; it was also shown that the received intensity over a one-way microwave transmission path would be an integrated measure of the rainfall intensity. Comparison between 10 cm (3000 mc) and 3 cm (10,000 mc) equipment for storm tracking was made through examination of PPI-scope photographs of a hurricane in the Gulf of Mexico (see Fig. 2), and it was concluded that the use of equipment operating near or at the higher frequency is the more desirable for this purpose because of higher definition, although not necessarily greater range, for the same radar peak pulse power and other factors.


AN/APS - 2F RADAR 3 000 MCS

AN/APS - 15 RADAR 10 000 MCS

Fig. 2--Comparison of two types of airborne radar during passage of hurricane; NAS, Corpus Christi, Texas, $17^{h}30^{m}$C, August 26, 1945; 50 mile sweep

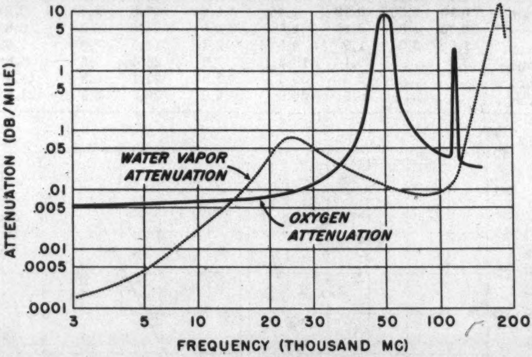


Fig. 3--Water vapor and oxygen attenuation

Attenuation due to oxygen and water vapor was discussed and illustrated by curves (see Fig. 3) which show the variation of attenuation with frequency. It was pointed out that such curves should be consulted before choice is made of a frequency for a particular operation, such as normal microwave communication, operation in which limited range is desired, and the measurement of the distribution of water vapor in the atmosphere. Mention was made of further uses of radar in meteorology; determination of in-flight winds if a plane is on instruments; structure of clouds, both horizontally and vertically; possible estimation of thunderstorm turbulence; and evaporation measurements.

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Washington 25, D. C.

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THE RECURRENCE TENDENCY AND FORECASTS OF MAGNETIC ACTIVITY

A. H. Shapley

Abstract--The recurrence tendency in magnetic character figures is evaluated by auto-correlation coefficients for various intervals up to 83 days for each year from 1890 to 1944. The strength of the 27-day recurrence pulse varies during the 55 years, being generally strong from about two years after sunspot maximum through the minimum year. Evidence for persistent recurrence intervals other than multiples of about 27 days is very weak. The magnitudes of the correlation coefficients for short intervals indicate that the time unit of geomagnetic activity is two to three days. Formulas for the prediction of magnetic character figures by the method of least squares are based on the mean auto-correlation coefficients for intervals of 1, 26, 27, 28, and 54 days for stages of the sunspot cycle with weak and strong recurrence conditions. A prediction formula with a non-linear term is also derived.

The recurrence tendency--The tendency for magnetically disturbed or quiet periods to repeat themselves at intervals of about 27, 54 or higher multiples of 27 days is not equally pronounced during the various stages of the solar cycle. Although CHREE and STAGG [see "References" at end of paper, 1927] found the tendency present in each of the years 1906 to 1925, the recurrence was better defined in the years of low sunspot activity and also in the years when the average sunspot latitude was low [see also ARCHENHOLD, 1939]. BARTELS [1932] points out the variability in the strength of the tendency as shown in his charts devised for this purpose. MAUNDER [1905], CHREE and STAGG [1927], and GREAVES and NEWTON [1929] all found that the recurrence tendency was stronger for the moderate types of magnetic disturbances than for the great storms. These results come from analyses by the superposed epoch method of CHREE [1912], in which by selecting disturbed (or quiet) days according to some criterion and computing the average magnetic activity ± n days from the selected day it is possible to show a recurrence tendency without involving a preconception of the length of the interval. Maunder, and Greaves and Newton used the amplitude of disturbance as the basis for selection of days, thereby including many data in years when many disturbances occurred but relatively few data in other years. Chree and Stagg, and Archenhold selected the five most disturbed days in each month, thus equalizing the data from each year, but varying the degree of storminess of the days selected. The former also made separate use of the five quietest days per month, the combination giving perhaps a more uniform body of data. The selection of days of comparable disturbance on the one hand gives an unequal distribution of selected days during the various phases of the cycle of solar or magnetic activity; on the other hand the selection of a uniform number of days each year throughout the cycle causes the degree of disturbance represented by the selected days to vary. Each method presents difficulties in evaluating the time variation of the recurrence tendency.

Evaluation of the recurrence tendency may be accomplished by calculating coefficients of linear correlation between the magnetic character figure for each day and the character figure for the nth succeeding day. Thus

$$r_{0,n} = \Sigma x_0 x_n / \sigma_0 \sigma_n$$

where $r_{0,n}$, the auto-correlation coefficient between day 0 and n, is derived from the character figures x expressed in units of their standard deviation σ. The recurrence measured in this way will apply for all character figures rather than for some designated degree of disturbance. Year to year comparison of the recurrence tendency is effected by calculation of the coefficients separately for each year. Auto-correlation coefficients showing this recurrence were computed for the International Magnetic Character Figures, C, which are listed by CHAPMAN and BARTELS [1940] for 1890 to 1937 and tabulated periodically in the Journal of Terrestrial Magnetism and Atmospheric Electricity for 1938 to 1944. The index C rates every day on a scale of increasing magnetic disturbance from 0.0 to 2.0, a range convenient for correlation analyses. The coefficients were computed for each year separately; thus each group has a sufficiently large population that, although the distribution of C-figures is not normal and varies slightly from year to year, regrouping seemed unnecesary. The computations were carried out by the Mendenhall-Warren-Hollerith correlation method, [WARREN and MENDENHALL, 1929], an exact method employing punch card

Table 1--Auto-correlation coefficients from magnetic character

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1890	49	17	05	06	07	07	09	03	$\overline{02}$	$\overline{12}$	$\overline{08}$	$\overline{06}$	$\overline{05}$	$\overline{05}$	$\overline{09}$	$\overline{11}$	$\overline{04}$	..	$\overline{02}$	04	01	..	$\overline{10}$
91	53	18	02	$\overline{08}$	$\overline{02}$	$\overline{04}$	$\overline{06}$	$\overline{07}$	$\overline{11}$	$\overline{05}$	$\overline{01}$	$\overline{01}$	$\overline{02}$	$\overline{05}$	$\overline{05}$	04	03	..	$\overline{04}$	$\overline{02}$	07	..	$\overline{03}$
92	49	16	03	03	05	$\overline{02}$	$\overline{10}$	$\overline{12}$	$\overline{10}$	$\overline{11}$	$\overline{07}$	06	08	07	05	05	10	..	$\overline{03}$	$\overline{03}$	$\overline{02}$	..	$\overline{04}$
93	49	19	03	$\overline{11}$	$\overline{14}$	$\overline{18}$	$\overline{10}$	$\overline{11}$	00	03	04	02	$\overline{07}$	$\overline{03}$	$\overline{06}$	$\overline{09}$	$\overline{08}$	..	$\overline{12}$	$\overline{15}$	$\overline{08}$	..	$\overline{03}$
94	48	14	01	06	05	01	04	01	$\overline{06}$	$\overline{11}$	$\overline{11}$	$\overline{13}$	$\overline{07}$	$\overline{11}$	$\overline{12}$	$\overline{09}$	$\overline{10}$	..	$\overline{07}$	$\overline{08}$	$\overline{05}$	..	$\overline{06}$
95	50	15	05	07	03	$\overline{05}$	$\overline{07}$	$\overline{04}$	$\overline{08}$	$\overline{06}$	$\overline{02}$	12	22	27	17	03	$\overline{01}$	..	$\overline{10}$	$\overline{10}$	$\overline{07}$	..	$\overline{08}$
96	54	27	10	00	$\overline{05}$	$\overline{09}$	$\overline{10}$	$\overline{05}$	$\overline{03}$	$\overline{03}$	$\overline{01}$	$\overline{05}$	$\overline{03}$	$\overline{01}$	00	$\overline{05}$	$\overline{08}$	..	$\overline{01}$	01	01	..	07
97	44	08	02	04	$\overline{01}$	$\overline{05}$	$\overline{04}$	$\overline{03}$	07	05	$\overline{01}$	$\overline{07}$	$\overline{11}$	$\overline{10}$	$\overline{07}$	05	04	..	$\overline{02}$	$\overline{03}$	$\overline{05}$	..	$\overline{06}$
98	50	17	12	07	01	$\overline{04}$	$\overline{09}$	$\overline{08}$	$\overline{17}$	$\overline{18}$	$\overline{15}$	$\overline{18}$	$\overline{16}$	$\overline{12}$	$\overline{13}$	$\overline{16}$	$\overline{14}$	..	$\overline{04}$	$\overline{10}$	$\overline{12}$	..	08
99	55	20	05	$\overline{06}$	$\overline{11}$	$\overline{13}$	$\overline{05}$	01	06	10	16	07	$\overline{01}$	05	03	$\overline{01}$	$\overline{01}$	..	$\overline{02}$	$\overline{12}$	$\overline{16}$	..	$\overline{10}$
1900	39	00	$\overline{04}$	10	22	24	20	02	$\overline{08}$	$\overline{05}$	$\overline{02}$	04	02	$\overline{01}$	$\overline{07}$	01	07	..	06	11	12	..	03
01	34	$\overline{01}$	$\overline{08}$	$\overline{13}$	$\overline{02}$	00	01	$\overline{04}$	$\overline{06}$	$\overline{07}$	$\overline{10}$	$\overline{02}$	00	$\overline{04}$	$\overline{05}$	$\overline{06}$	$\overline{02}$	..	$\overline{08}$	06	08	..	$\overline{07}$
02	42	07	$\overline{07}$	$\overline{12}$	$\overline{19}$	$\overline{17}$	$\overline{11}$	$\overline{08}$	$\overline{05}$	01	$\overline{05}$	$\overline{04}$	$\overline{01}$	$\overline{02}$	$\overline{07}$	02	02	..	00	$\overline{13}$	$\overline{16}$	..	$\overline{04}$
03	48	12	04	00	$\overline{03}$	02	04	08	06	06	05	05	02	$\overline{02}$	02	06	16	..	12	06	04	..	00
04	43	04	$\overline{11}$	$\overline{13}$	$\overline{08}$	01	04	00	02	$\overline{05}$	$\overline{03}$	$\overline{01}$	$\overline{02}$	01	$\overline{04}$	$\overline{03}$	$\overline{04}$	..	$\overline{02}$	05	01	..	$\overline{06}$
05	48	15	01	$\overline{02}$	01	00	02	02	08	04	02	$\overline{02}$	$\overline{08}$	$\overline{05}$	$\overline{03}$	$\overline{02}$	02	..	02	04	01	..	$\overline{09}$
06	48	07	$\overline{07}$	$\overline{04}$	01	03	05	06	04	$\overline{05}$	$\overline{10}$	$\overline{10}$	$\overline{04}$	$\overline{01}$	$\overline{02}$	$\overline{01}$	05	..	11	10	$\overline{02}$	..	$\overline{12}$
07	47	09	$\overline{03}$	$\overline{13}$	$\overline{09}$	$\overline{03}$	$\overline{06}$	$\overline{10}$	$\overline{06}$	$\overline{07}$	$\overline{05}$	$\overline{03}$	12	09	05	04	$\overline{07}$	..	$\overline{07}$	$\overline{03}$	$\overline{03}$	..	$\overline{08}$
08	57	19	$\overline{02}$	$\overline{09}$	$\overline{04}$	07	07	06	03	00	$\overline{11}$	$\overline{13}$	$\overline{14}$	$\overline{17}$	$\overline{21}$	$\overline{12}$	06	..	11	00	$\overline{03}$	..	$\overline{03}$
09	52	19	07	14	00	$\overline{04}$	$\overline{03}$	$\overline{09}$	$\overline{12}$	$\overline{17}$	$\overline{18}$	$\overline{14}$	$\overline{14}$	$\overline{11}$	$\overline{08}$	$\overline{07}$	$\overline{10}$	..	$\overline{15}$	$\overline{08}$	02	..	07
1910	52	19	05	$\overline{04}$	$\overline{05}$	$\overline{05}$	$\overline{01}$	01	00	$\overline{02}$	01	03	02	07	06	02	$\overline{05}$	..	$\overline{11}$	$\overline{06}$	$\overline{04}$	..	$\overline{02}$
11	50	12	02	05	13	09	07	05	$\overline{01}$	01	00	$\overline{10}$	$\overline{18}$	$\overline{14}$	$\overline{07}$	$\overline{01}$	$\overline{02}$	..	07	17	15	..	08
12	43	01	$\overline{12}$	$\overline{08}$	04	$\overline{01}$	$\overline{04}$	$\overline{11}$	$\overline{10}$	$\overline{07}$	$\overline{04}$	$\overline{04}$	$\overline{09}$	$\overline{15}$	$\overline{12}$	$\overline{07}$	$\overline{03}$	..	$\overline{09}$	02	10	..	$\overline{05}$
13	51	22	06	$\overline{04}$	01	$\overline{05}$	$\overline{06}$	$\overline{11}$	$\overline{11}$	$\overline{11}$	$\overline{10}$	$\overline{08}$	$\overline{06}$	$\overline{06}$	$\overline{10}$	$\overline{11}$	$\overline{07}$	..	$\overline{07}$	$\overline{05}$	$\overline{05}$	..	01
14	42	09	$\overline{04}$	$\overline{02}$	04	06	05	04	$\overline{02}$	$\overline{03}$	02	$\overline{01}$	$\overline{01}$	$\overline{09}$	$\overline{09}$	$\overline{13}$	$\overline{07}$	..	$\overline{03}$	06	01	..	$\overline{04}$
15	52	14	10	12	05	$\overline{07}$	$\overline{11}$	$\overline{08}$	$\overline{05}$	$\overline{01}$	00	$\overline{04}$	$\overline{05}$	$\overline{02}$	01	03	01	..	$\overline{09}$	$\overline{10}$	$\overline{06}$	..	03
16	51	12	$\overline{01}$	$\overline{04}$	$\overline{05}$	$\overline{07}$	$\overline{02}$	$\overline{06}$	$\overline{06}$	$\overline{09}$	$\overline{09}$	$\overline{03}$	07	11	03	$\overline{08}$	$\overline{14}$	..	$\overline{04}$	04	03	..	$\overline{09}$
17	47	12	$\overline{04}$	$\overline{15}$	$\overline{15}$	$\overline{13}$	$\overline{08}$	$\overline{02}$	03	02	$\overline{01}$	02	06	07	06	04	04	..	00	$\overline{01}$	$\overline{09}$	..	$\overline{14}$
18	56	17	02	$\overline{03}$	$\overline{07}$	$\overline{10}$	$\overline{11}$	$\overline{08}$	$\overline{14}$	$\overline{12}$	$\overline{04}$	02	00	01	05	07	02	..	$\overline{06}$	$\overline{12}$	$\overline{11}$	..	04
19	47	07	$\overline{07}$	$\overline{09}$	$\overline{12}$	$\overline{13}$	$\overline{04}$	$\overline{07}$	$\overline{03}$	$\overline{03}$	03	05	04	08	08	08	03	..	02	02	04	..	$\overline{11}$
1920	44	10	$\overline{11}$	$\overline{15}$	$\overline{12}$	$\overline{04}$	$\overline{07}$	01	09	04	00	05	02	00	$\overline{07}$	$\overline{07}$	$\overline{01}$	..	02	$\overline{01}$	$\overline{02}$	..	00
21	50	15	12	04	06	04	$\overline{02}$	$\overline{09}$	$\overline{06}$	$\overline{04}$	$\overline{11}$	$\overline{09}$	$\overline{07}$	$\overline{11}$	$\overline{05}$	$\overline{01}$	$\overline{11}$	..	$\overline{04}$	02	$\overline{04}$	..	04
22	54	22	02	$\overline{09}$	$\overline{20}$	$\overline{20}$	$\overline{09}$	$\overline{09}$	$\overline{07}$	03	08	17	17	21	20	11	04	..	$\overline{11}$	$\overline{13}$	$\overline{14}$	..	$\overline{10}$
23	54	15	$\overline{06}$	$\overline{15}$	$\overline{21}$	$\overline{20}$	$\overline{12}$	$\overline{08}$	00	02	01	$\overline{06}$	$\overline{05}$	$\overline{02}$	08	12	17	..	$\overline{02}$	$\overline{09}$	$\overline{07}$	..	$\overline{13}$
24	46	14	$\overline{01}$	$\overline{05}$	$\overline{08}$	$\overline{03}$	02	$\overline{05}$	$\overline{06}$	$\overline{08}$	$\overline{06}$	$\overline{03}$	$\overline{05}$	$\overline{05}$	$\overline{10}$	$\overline{09}$	$\overline{08}$	..	05	$\overline{03}$	$\overline{03}$	..	$\overline{09}$
25	45	07	07	03	$\overline{01}$	$\overline{10}$	$\overline{06}$	$\overline{05}$	00	04	01	02	04	06	03	00	02	..	$\overline{01}$	$\overline{01}$	$\overline{01}$	..	09
26	54	19	09	08	05	05	10	11	04	$\overline{01}$	00	06	01	$\overline{06}$	$\overline{06}$	$\overline{07}$	$\overline{11}$	..	$\overline{01}$	$\overline{01}$	00	..	04
27	53	21	06	03	$\overline{01}$	$\overline{07}$	$\overline{11}$	$\overline{10}$	02	09	06	06	04	04	07	05	02	..	$\overline{04}$	$\overline{05}$	$\overline{06}$	..	$\overline{09}$
28	54	19	06	$\overline{03}$	02	02	$\overline{04}$	$\overline{04}$	$\overline{11}$	$\overline{06}$	00	$\overline{04}$	$\overline{05}$	$\overline{02}$	03	06	01	..	$\overline{01}$	$\overline{02}$	$\overline{01}$	..	10
29	55	17	05	05	05	$\overline{01}$	$\overline{09}$	$\overline{08}$	$\overline{06}$	02	08	12	14	09	04	03	00	..	$\overline{11}$	$\overline{10}$	$\overline{08}$	..	$\overline{09}$
1930	62	25	08	$\overline{04}$	$\overline{14}$	$\overline{20}$	$\overline{17}$	$\overline{18}$	02	06	05	16	17	14	14	09	01	..	$\overline{12}$	$\overline{15}$	$\overline{16}$	..	$\overline{09}$
31	55	19	$\overline{04}$	$\overline{14}$	$\overline{07}$	$\overline{03}$	01	09	07	10	14	05	05	02	06	13	17	..	08	$\overline{07}$	$\overline{11}$	..	$\overline{06}$
32	60	27	05	$\overline{08}$	$\overline{14}$	$\overline{16}$	$\overline{14}$	$\overline{07}$	02	05	05	02	$\overline{02}$	$\overline{02}$	04	04	04	..	$\overline{09}$	$\overline{11}$	$\overline{14}$	..	00
33	60	29	12	07	04	$\overline{03}$	$\overline{05}$	$\overline{12}$	$\overline{18}$	$\overline{18}$	$\overline{18}$	$\overline{05}$	00	$\overline{01}$	$\overline{08}$	$\overline{11}$	$\overline{18}$	..	$\overline{12}$	$\overline{11}$	$\overline{07}$	..	$\overline{03}$
34	46	15	07	03	02	05	$\overline{01}$	$\overline{04}$	$\overline{07}$	$\overline{04}$	$\overline{09}$	$\overline{14}$	$\overline{06}$	$\overline{06}$	$\overline{06}$	$\overline{05}$	00	..	$\overline{01}$	02	05	..	02
35	51	19	06	$\overline{04}$	$\overline{03}$	00	$\overline{03}$	$\overline{04}$	$\overline{04}$	00	02	$\overline{02}$	05	00	$\overline{01}$	00	$\overline{04}$	..	03	$\overline{04}$	$\overline{04}$	..	$\overline{06}$
36	48	20	09	02	01	01	03	$\overline{02}$	$\overline{06}$	$\overline{03}$	$\overline{07}$	$\overline{10}$	$\overline{14}$	$\overline{08}$	$\overline{06}$	$\overline{08}$	$\overline{01}$	..	$\overline{08}$	$\overline{07}$	02	..	10
37	48	15	09	07	00	$\overline{08}$	$\overline{04}$	$\overline{03}$	04	00	00	02	05	$\overline{01}$	$\overline{02}$	$\overline{02}$	$\overline{06}$	..	$\overline{11}$	$\overline{09}$	$\overline{12}$	..	$\overline{05}$
38	54	26	12	03	$\overline{01}$	$\overline{03}$	$\overline{06}$	$\overline{06}$	$\overline{09}$	$\overline{09}$	$\overline{09}$	$\overline{10}$	$\overline{16}$	$\overline{12}$	$\overline{07}$	$\overline{04}$	01	..	09	05	00	..	19
39	52	16	03	00	08	11	06	02	$\overline{11}$	$\overline{10}$	$\overline{01}$	06	08	08	00	$\overline{07}$	$\overline{04}$	..	$\overline{02}$	$\overline{02}$	02	..	$\overline{02}$
1940	54	18	07	08	07	04	00	00	02	02	$\overline{05}$	$\overline{09}$	$\overline{19}$	$\overline{27}$	$\overline{27}$	$\overline{20}$	$\overline{14}$	..	$\overline{05}$	$\overline{03}$	$\overline{05}$	..	$\overline{09}$
41	50	18	00	$\overline{08}$	$\overline{08}$	$\overline{06}$	$\overline{06}$	$\overline{02}$	$\overline{02}$	$\overline{01}$	$\overline{03}$	$\overline{06}$	$\overline{07}$	$\overline{04}$	$\overline{05}$	03	09	..	07	09	07	..	00
42	49	18	11	07	06	$\overline{03}$	$\overline{09}$	$\overline{08}$	00	02	$\overline{03}$	09	18	15	08	11	01	..	$\overline{12}$	$\overline{13}$	$\overline{06}$	..	$\overline{05}$
43	63	33	16	15	09	01	$\overline{12}$	$\overline{16}$	$\overline{21}$	$\overline{13}$	$\overline{05}$	00	$\overline{02}$	$\overline{04}$	00	$\overline{09}$	$\overline{09}$	..	$\overline{14}$	09	$\overline{02}$	..	11
44	50	24	23	14	12	13	01	$\overline{05}$	$\overline{07}$	$\overline{01}$	$\overline{08}$	$\overline{05}$	01	01	$\overline{02}$	$\overline{10}$	$\overline{13}$	..	$\overline{06}$	03	10	..	16

figures (multiplied by 100; negative values overscored)

24	25	26	27	28	29	30	31	32	33	34	35	36	52	53	54	55	56	79	80	81	82	83
$\overline{03}$	05	18	28	35	28	18	09	09	11	09	04	04	$\overline{11}$	$\overline{10}$	01	03	11	$\overline{15}$	$\overline{11}$	$\overline{10}$	$\overline{10}$	$\overline{03}$
00	04	12	20	23	19	08	$\overline{01}$	00	$\overline{03}$	$\overline{11}$	$\overline{15}$	$\overline{07}$	$\overline{02}$	$\overline{06}$	$\overline{10}$	$\overline{06}$	$\overline{02}$	$\overline{03}$	$\overline{08}$	$\overline{12}$	$\overline{11}$	07
$\overline{07}$	$\overline{02}$	$\overline{01}$	05	04	07	04	$\overline{03}$	$\overline{07}$	$\overline{11}$	$\overline{09}$	$\overline{13}$	$\overline{15}$	00	07	16	17	15	07	05	12	19	12
05	10	15	22	16	12	05	$\overline{03}$	$\overline{03}$	$\overline{03}$	$\overline{04}$	$\overline{03}$	01	08	12	09	11	11	04	12	14	12	00
$\overline{05}$	06	13	11	04	07	12	09	02	$\overline{02}$	$\overline{02}$	$\overline{05}$	$\overline{10}$	07	11	16	17	13	$\overline{02}$	$\overline{04}$	$\overline{03}$	00	03
$\overline{01}$	12	28	38	33	21	10	00	$\overline{06}$	$\overline{10}$	$\overline{10}$	$\overline{07}$	$\overline{07}$	06	15	26	28	17	10	16	17	16	20
13	23	35	44	43	31	12	$\overline{06}$	$\overline{10}$	$\overline{13}$	$\overline{16}$	$\overline{11}$	$\overline{01}$	18	25	23	27	21	12	10	13	13	07
00	09	22	27	19	04	06	02	00	01	02	03	05	03	19	22	12	05	15	18	13	$\overline{05}$	$\overline{11}$
13	16	30	44	37	22	14	08	05	$\overline{04}$	$\overline{07}$	$\overline{08}$	$\overline{16}$	15	20	26	23	14	09	12	12	16	15
$\overline{05}$	10	28	39	28	12	00	$\overline{10}$	$\overline{12}$	$\overline{14}$	$\overline{14}$	$\overline{12}$	$\overline{02}$	10	20	31	26	17	04	12	18	14	10
00	14	24	18	12	06	06	05	10	11	05	01	$\overline{01}$	12	23	20	10	07	00	11	09	03	$\overline{02}$
$\overline{17}$	$\overline{08}$	17	28	25	22	00	$\overline{06}$	$\overline{07}$	04	10	$\overline{01}$	$\overline{15}$	$\overline{07}$	06	20	25	06	$\overline{02}$	10	22	20	11
$\overline{03}$	$\overline{01}$	10	20	24	16	08	03	00	$\overline{07}$	$\overline{11}$	$\overline{15}$	$\overline{11}$	$\overline{12}$	$\overline{07}$	00	10	16	$\overline{08}$	$\overline{10}$	02	04	03
06	13	20	26	27	16	11	01	05	18	09	01	05	05	12	18	18	15	07	08	12	10	08
$\overline{04}$	00	07	12	08	06	$\overline{02}$	$\overline{05}$	$\overline{02}$	00	04	00	$\overline{09}$	$\overline{02}$	03	02	$\overline{02}$	$\overline{02}$	03	05	06	$\overline{04}$	$\overline{11}$
$\overline{08}$	01	08	20	18	14	19	08	06	01	$\overline{11}$	$\overline{12}$	$\overline{09}$	$\overline{08}$	$\overline{04}$	00	09	07	$\overline{10}$	$\overline{06}$	$\overline{02}$	05	06
$\overline{05}$	01	09	17	13	03	$\overline{08}$	$\overline{13}$	$\overline{14}$	$\overline{05}$	02	$\overline{01}$	$\overline{04}$	03	08	12	14	08	13	11	09	01	03
$\overline{04}$	09	17	17	10	06	08	03	$\overline{05}$	$\overline{04}$	$\overline{06}$	$\overline{08}$	$\overline{11}$	00	08	09	08	04	00	01	$\overline{01}$	01	02
07	17	29	29	20	08	02	00	05	07	05	02	$\overline{01}$	14	16	12	09	09	16	19	16	07	08
04	$\overline{02}$	10	20	22	13	09	02	02	01	03	$\overline{01}$	$\overline{04}$	08	10	14	08	08	$\overline{01}$	00	$\overline{02}$	$\overline{02}$	04
$\overline{02}$	06	24	32	24	15	08	05	$\overline{03}$	$\overline{03}$	01	03	07	00	08	15	14	09	$\overline{15}$	$\overline{09}$	02	08	06
09	19	35	46	37	16	06	05	06	08	06	02	00	13	31	41	28	10	01	13	24	26	09
$\overline{09}$	04	25	33	17	02	$\overline{06}$	$\overline{06}$	02	09	04	$\overline{08}$	$\overline{13}$	10	26	29	14	03	04	14	12	03	$\overline{02}$
07	21	34	38	32	21	10	07	02	$\overline{08}$	$\overline{09}$	$\overline{10}$	$\overline{14}$	01	11	14	16	09	07	10	08	01	$\overline{09}$
$\overline{01}$	06	04	04	10	14	10	13	10	02	02	10	$\overline{02}$	$\overline{04}$	00	04	06	$\overline{02}$	$\overline{03}$	02	$\overline{08}$	$\overline{02}$	03
10	13	20	30	27	17	10	09	00	$\overline{11}$	$\overline{12}$	$\overline{10}$	$\overline{08}$	08	09	14	18	16	00	03	03	06	06
$\overline{10}$	$\overline{08}$	00	12	09	01	$\overline{09}$	$\overline{06}$	$\overline{02}$	$\overline{04}$	$\overline{01}$	04	00	07	15	15	13	11	$\overline{04}$	04	04	01	$\overline{03}$
$\overline{08}$	05	14	13	07	05	$\overline{04}$	$\overline{18}$	$\overline{19}$	$\overline{11}$	$\overline{05}$	$\overline{03}$	$\overline{04}$	13	12	08	04	$\overline{03}$	02	$\overline{05}$	$\overline{11}$	$\overline{16}$	$\overline{10}$
10	17	23	23	18	07	02	$\overline{04}$	$\overline{11}$	$\overline{12}$	$\overline{07}$	$\overline{11}$	$\overline{10}$	12	21	27	20	06	03	04	08	11	07
$\overline{09}$	02	16	20	15	08	$\overline{01}$	$\overline{04}$	01	02	$\overline{04}$	$\overline{07}$	$\overline{05}$	$\overline{09}$	00	11	05	$\overline{03}$	$\overline{03}$	04	04	$\overline{01}$	$\overline{04}$
02	03	17	26	17	02	$\overline{05}$	$\overline{04}$	$\overline{02}$	08	$\overline{08}$	$\overline{01}$	04	$\overline{02}$	05	08	05	00	$\overline{01}$	$\overline{04}$	$\overline{12}$	$\overline{05}$	$\overline{04}$
08	11	12	13	13	09	04	$\overline{02}$	$\overline{02}$	03	$\overline{04}$	04	09	10	08	09	11	02	07	04	02	$\overline{03}$	$\overline{08}$
03	21	39	46	36	25	09	$\overline{08}$	$\overline{18}$	$\overline{16}$	$\overline{14}$	$\overline{11}$	$\overline{04}$	17	30	37	38	22	10	22	31	30	18
$\overline{07}$	09	24	39	23	$\overline{01}$	$\overline{17}$	$\overline{19}$	$\overline{15}$	$\overline{13}$	$\overline{04}$	03	08	04	19	26	13	$\overline{02}$	07	12	10	$\overline{05}$	$\overline{12}$
$\overline{09}$	01	17	22	18	12	05	$\overline{02}$	00	$\overline{01}$	$\overline{03}$	$\overline{04}$	$\overline{04}$	03	12	10	07	02	08	17	18	09	$\overline{04}$
07	04	10	13	12	14	10	08	00	$\overline{07}$	$\overline{09}$	$\overline{08}$	$\overline{04}$	11	01	04	11	06	14	11	09	12	15
$\overline{01}$	08	16	24	22	12	00	$\overline{07}$	$\overline{02}$	07	16	17	13	00	$\overline{01}$	$\overline{02}$	05	06	03	02	03	06	08
$\overline{08}$	05	13	11	07	06	02	$\overline{08}$	$\overline{13}$	$\overline{15}$	$\overline{11}$	$\overline{06}$	$\overline{02}$	11	13	12	04	$\overline{12}$	05	09	$\overline{02}$	$\overline{14}$	$\overline{11}$
13	11	11	11	12	10	03	$\overline{07}$	$\overline{08}$	$\overline{05}$	$\overline{06}$	$\overline{07}$	$\overline{03}$	08	12	14	11	09	09	00	$\overline{02}$	01	00
$\overline{06}$	02	17	19	09	03	09	06	01	$\overline{04}$	$\overline{07}$	$\overline{07}$	$\overline{08}$	04	13	09	$\overline{01}$	$\overline{05}$	13	13	05	$\overline{06}$	08
03	26	49	55	47	33	12	$\overline{04}$	$\overline{17}$	$\overline{24}$	$\overline{22}$	$\overline{16}$	$\overline{09}$	20	38	48	44	34	11	30	41	41	25
02	15	34	44	32	14	01	$\overline{04}$	$\overline{03}$	$\overline{04}$	$\overline{01}$	05	12	08	22	28	22	05	04	13	15	10	03
11	21	39	47	39	18	00	$\overline{07}$	$\overline{12}$	$\overline{13}$	$\overline{13}$	$\overline{05}$	04	15	26	36	27	22	04	11	16	12	04
07	22	41	52	29	31	19	11	05	01	$\overline{04}$	$\overline{09}$	$\overline{19}$	12	24	32	29	17	00	12	16	14	08
09	1-	19	20	21	14	08	02	$\overline{05}$	$\overline{02}$	00	$\overline{07}$	$\overline{18}$	00	00	09	04	$\overline{01}$	$\overline{10}$	$\overline{09}$	00	03	00
$\overline{06}$	$\overline{01}$	06	17	21	24	13	03	00	03	05	$\overline{07}$	$\overline{06}$	$\overline{06}$	$\overline{08}$	$\overline{04}$	07	14	$\overline{01}$	00	03	04	02
12	12	18	23	23	23	12	11	09	02	00	$\overline{04}$	$\overline{09}$	01	07	06	07	11	08	04	01	06	05
$\overline{06}$	$\overline{05}$	$\overline{01}$	02	06	05	07	03	00	00	$\overline{06}$	$\overline{13}$	$\overline{13}$	$\overline{04}$	00	00	$\overline{01}$	04	$\overline{01}$	03	14	09	11
14	14	08	04	04	02	$\overline{06}$	$\overline{02}$	03	$\overline{03}$	$\overline{16}$	$\overline{18}$	$\overline{17}$	02	$\overline{06}$	$\overline{01}$	03	04	09	05	07	05	06
$\overline{01}$	03	20	29	20	05	$\overline{02}$	04	06	04	01	$\overline{09}$	$\overline{10}$	14	23	24	15	06	16	17	16	09	03
$\overline{04}$	08	13	20	17	13	03	$\overline{02}$	$\overline{10}$	$\overline{09}$	$\overline{05}$	$\overline{03}$	01	06	16	21	22	19	06	09	07	10	14
$\overline{03}$	12	23	29	21	04	$\overline{12}$	$\overline{16}$	$\overline{19}$	$\overline{12}$	$\overline{04}$	$\overline{01}$	08	02	13	22	13	$\overline{01}$	$\overline{02}$	01	06	01	$\overline{09}$
$\overline{03}$	11	31	31	21	09	11	07	$\overline{05}$	$\overline{14}$	$\overline{17}$	$\overline{21}$	$\overline{12}$	$\overline{01}$	09	12	10	13	$\overline{09}$	01	$\overline{01}$	$\overline{02}$	04
15	27	42	48	43	28	18	10	01	$\overline{05}$	$\overline{12}$	$\overline{19}$	$\overline{21}$	27	36	35	36	31	23	26	28	27	26
18	24	24	27	27	20	11	02	$\overline{07}$	$\overline{01}$	$\overline{03}$	$\overline{10}$	$\overline{12}$	20	21	18	19	17	13	16	16	14	11

machines. The correlation coefficients for 1-, 2-, 3-, . . . 36-day intervals (with the exception of 18- and 22-) and for 52-, 53-, . . . 56- and 79-, 80-, . . . 83-day intervals for each year 1890 to 1944 are listed in Table 1. Negative coefficients are overscored and all coefficients for convenience are multiplied by 100. Since the correlation coefficients were computed for several intervals simultaneously, the "year" for which recurrence was measured does not always correspond to the calendar year, the difference being as much as 35 days in addition to the length of the interval. The initial days of the 27-, 54-, and 8-day intervals, however, comprise a calendary year. The errors thus introduced are unimportant since the coefficients will not be treated separately.

The characteristics of the recurrence tendency of magnetic activity are well demonstrated by these auto-correlation coefficients. Figure 1 shows the variation in the strength of the tendency during the 55 years, represented by the annual coefficients for the 27-day interval; these are the largest in the first recurrence pulse in more than 80 per cent of the individual years. The cyclic variation of the recurrence tendency is more apparent if this curve is smoothed according to $r_0 = (r_{-1} + 2r_0 + r_{+1})/4$ (where the subscripts refer to years) as in Figure 2A. We recall that the division of the data into approximately calendar years was arbitrary. The recurrence cycle is approximately 180 degrees out of phase with the curve of sunspot numbers (see Fig. 2B) and also with the curve of the μ-measure of magnetic activity (Fig. 2C), but evidently closely related to both. The recurrence cycle and the annual percentage of low latitude sunspots $(\leq 10^\circ)$ compiled from the Greenwich publications, are remarkably similar. The correlation between the unsmoothed 27-day recurrence and the others is $r = -0.56$, -0.40, and $+0.52$, respectively.

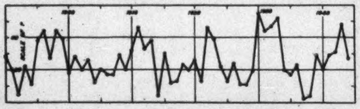

Fig. 1--27-day recurrence correlation coefficients, 1890-1944

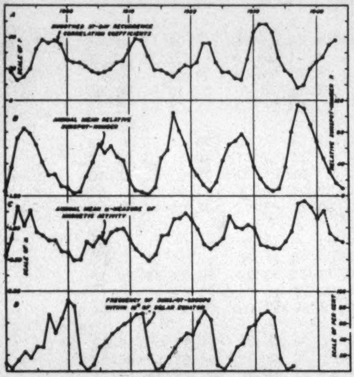

Fig. 2--Comparison of data relative to 27-day recurrence tendency, 1890-1944

To study variation in strength of recurrence during a single solar cycle, we may consider the average cycle to be made up of three years between minimum and maximum year and six between maximum and minimum, typical for the last eight sunspot cycles. Averaging the 27-day recurrence coefficients for the maximum and minimum years and distributing the coefficients of the remainder of the years proportionately according to this scheme, we obtain Figure 3, which shows that recurrence is most pronounced about a year before minimum. It is generally strong from about two years after maximum through the minimum year, and generally weak during the remainder of the cycle. For comparison, the annual sunspot numbers are also shown in Figure 3 for the same period, combined in the same way.

The variation from year to year of the smoothed coefficients for 54- and 81-day intervals follows closely that for the 27-day interval (see Fig. 4). The relative magnitudes of the 0-, 27-, 54-, and 81-day recurrence pulses for the stages strong and weak recurrence are shown in Figure 5.

Existence of any significant recurrence intervals other than about 27-days or multiples thereof should be detectable in the results given in Table 1. The annual coefficients for all intervals are averaged in Figure 6 for four periods of sunspot activity . . . minimum (calendar year of epoch ± one year), maximum, and the intervening ascending and descending years of the sunspot cycle. The very strong maximum in the coefficients at about 27 days is clearly shown, but no other pronounced maximum is revealed. In the descending and minimum periods of solar activity the coefficients for 13-, 14-, and 15-day intervals are slightly larger than on adjacent days, about zero instead of slightly negative. Reference to Table 1 shows that in a few individual years, for instance 1895, 1922, 1930, and 1942, the coefficients were higher than average at about these intervals. Possibly this illustrates a tendency for active solar regions to be situated 180 degrees apart in longitude at these stages of the solar cycle. A few coefficients of distinctly above average

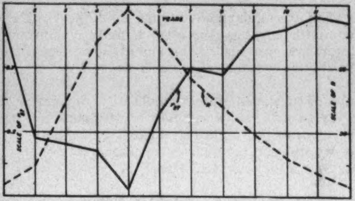

Fig. 3--27-day recurrence coefficients (r_{27}) and sunspot numbers (R) for a typical 11-year cycle

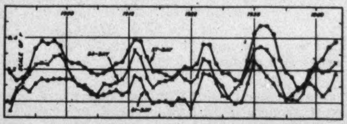

Fig. 4--Smoothed recurrence coefficients for 27-, 54-, and 81-day intervals, 1890-1944

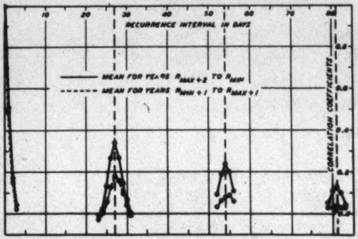

Fig. 5--First, second, and third recurrence pulses in years of strong and weak recurrence correlation

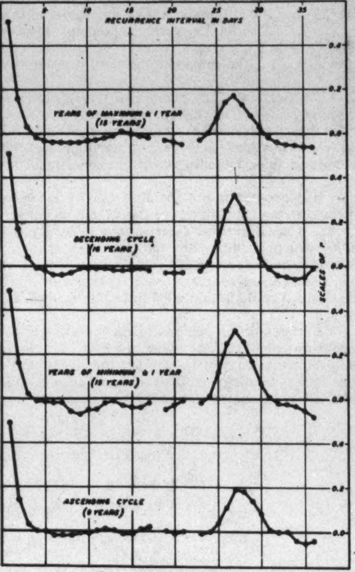

Fig. 6--Recurrence of magnetic C-figures at four stages of solar cycle; average of yearly correlation coefficients

value for intervals other than those of recognized recurrence appear in Table 1, such as for the six-day interval in 1900, the 20-day interval in 1911, and the 17-day interval in 1931. The evidence for consistent recurrence intervals other than those of about 27 days or multiples thereof is very weak; certainly no other interval is a rival in strength and prominence.

Consideration of the one-, two-, and three-day recurrence coefficients (see Table 1 and Fig. 6), shows that there is a very high correlation between the magnetic activity of one day and the first following, a much lower correlation with the second and very little with the third. Thus, the time unit of geomagnetic activity would seem to be on the average two to three days. Because intervals are considered, the initial part of the curve of Figure 6 is not doubled back on itself in order to find the average length of a disturbance. The two- to three-day geomagnetic time unit suggests, for instance, that forecasts of magnetic activity should not be made for daily intervals; preferably three-day average character figure estimates should be attempted.

Application to prediction--The correlation coefficients discussed in the preceding section may be applied to the prediction of magnetic character figures, in particular to the prediction of magnetic storms and the closely allied ionospheric disturbances. The problem is to predict a character figure, $x'_0 = ax_1 + bx_2 + \ldots$, for the value x_0, from the character figures of several previous days, $x_1, x_2 \ldots$, such that the squares of the errors of a large number of predictions, $\Sigma(x_0 - x'_0)^2$, is a minimum. Substituting and differentiating with respect to the unknown constants, a, b, . . ., we have as the required conditions

$$\Sigma(x_0x_1 - ax_1^2 - bx_1x_2 - cx_1x_3 - \ldots) = 0$$
$$\Sigma(x_0x_2 - ax_1x_2 - bx_2^2 - cx_2x_3 - \ldots) = 0 \text{ etc.}$$

If the character figures, x, are measured in terms of their standard deviations, then $\Sigma x_1^2/N = \Sigma x_2^2/N = \ldots = 1$. Likewise $\Sigma x_0 x_1/N$ is the auto-correlation coefficient, $r_{0,1}$, between x_0 and x_1; similarly $\Sigma x_0 x_2/N$ is $r_{0,2}$, etc. Given the correlation coefficients, we may solve the simultaneous equations for a, b, . . ., the constants for the least squares prediction formula $x_0' = ax_1 + bx_2 + \ldots$

Theoretically any number of terms may be included in a prediction formula. The accuracy of the prediction is not necessarily reduced by the inclusion of terms with small coefficients, or, in other words, terms based on weak correlation. The labor of solving a large number of simultaneous equations, however, is considerable, and so we will confine ourselves to formulas of five terms or less, including the more significant recurrence intervals of 1, 26, 27, 28, and 54 days.

The prediction method may also be extended to include nonlinear terms, for instance ones involving the consistency of the 27-day recurrence sequence of which the predicted day is a member. Thus, if the character figures on both the 27 and 54 preceding days were small, one might expect a greater probability that the character of the "zero" day will also be small. Accordingly disturbance indices $C_\alpha = \sqrt{(C_{-27} \times C_{-54})}$ and $C_\beta = \sqrt{(C_{-27} \times C_{-81})}$ were derived for each day, and $r_{0,\alpha}$, $r_{0,\beta}$ and the appropriate cross-correlation coefficients were computed so that terms involving x_α and x_β could be included in prediction formulas with x_{26}, x_{27}, and so forth.

Because of the demonstrated variation in the strength of recurrence with the solar cycle, separate prediction formulas are given for the stages of strong and weak recurrence. The average auto-correlation coefficients for the significant recurrence-intervals and $r_{0,\alpha}$ and $r_{0,\beta}$ are given for each subdivision of the cycle in Table 2. With these and the required cross-correlation coefficients, prediction formulas applicable to years of strong (1) and weak (2) recurrence are:

$$x'_0 = 0.23\bar{x} + 0.44x_1 + 0.11x_{26} + 0.12x_{27} + 0.02x_{28} + 0.08x_{54} \qquad \text{(A1)}$$

$$x'_0 = 0.33\bar{x} + 0.47x_1 + 0.06x_{26} + 0.07x_{27} + 0.03x_{28} + 0.04x_{54} \qquad \text{(A2)}$$

$$x'_0 = 0.46\bar{x} + 0.13x_{26} + 0.17x_{27} + 0.13x_{28} + 0.11x_{54} \qquad \text{(B1)}$$

$$x'_0 = 0.71\bar{x} + 0.06x_{26} + 0.09x_{27} + 0.10x_{28} + 0.04x_{54} \qquad \text{(B2)}$$

$$x'_0 = 0.49\bar{x} + 0.14x_{26} + 0.07x_{27} + 0.13x_{28} + 0.17x_{\alpha} \qquad \text{(C1)}$$

Table 2--Average auto-correlation coefficients for significant intervals in years of strong and weak recurrence condition

Type of year	Recurrence interval in days							
	1	26	27	28	54	81	α	β
Strong recurrence	0.51	0.27	0.34	0.27	0.24	0.13	0.35	0.28
Weak recurrence	0.49	0.13	0.18	0.16	0.08	0.04	0.18	0.15

The subscripts refer, of course, to preceding days, and α is as defined above. The units of x are those of the magnetic character figures, since conversion from units of standard deviation is effected by the term in $\bar{x}$, the mean value of the character figures, whose coefficient is $1 - (a + b + \ldots)$.

In formula (C1) the effect of the strong 27-day recurrence correlation is shared by x_{27} and x_α. Because the non-linear term receives the greater weight, we may infer that our supposition is valid that the consistency of the 27-day recurrence sequence has importance in prediction. In a formula like (C1), but also including a term in x_β, the coefficient in that term proved to be slightly negative. The coefficient of $\bar{x}$, however, was the same as in formula (C1), so we may conclude that x_β, though closely correlated with x_0, was entirely dependent on x_{27} and x_α and therefore contributed nothing of its own to the prediction.

The usefulness as well as the limitations of this method of predicting magnetic character figures is illustrated by trial predictions in typical years of strong and weak recurrence. Correlation of observed character figures with the predictions made by formula (A1) for 1944 gave r = 0.56 (see Fig. 7), by formula (B1), r = 0.37, while for the same period the simple 27-day correlation coefficient, $r_{0,27} = 0.31$. Predictions by formula (B2) for 1945 compared with observed values gave r = 0.17, when $r_{0,27} = 0.14$. The prediction formulas work out better than simple 27-day predictions as expected, the improvement being obtained mainly by including in the prediction data

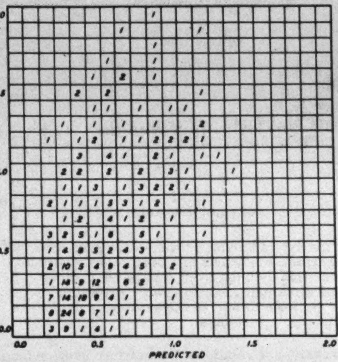

Fig. 7--Correlation diagram of magnetic character figures, 1944, observed and predicted by Formula A1; r = 0.56

from the day first preceding the predicted one. Regression towards the mean limits the range of the predicted character figures such that the predictions for years of weak recurrence lack detail. Independent correlations of some magnitude used in the formulas will increase the range and accuracy of the predictions. It might be expected, for instance, that other relationships such as solar-geomagnetic correlations could be used for more reliable prediction formulas.

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Transactions, American Geophysical Union Volume 28, Number 5 October 1947

INVESTIGATION OF UNDERWATER PRESSURE RECORDS AND SIMULTANEOUS SEA SURFACE PATTERNS

H. R. Seiwell

(Contribution No. 386, Woods Hole Oceanographic Institution)

Abstract--An investigation to determine the extent to which underwater pressure recordings may be used to characterize sea-surface conditions has been in process during the past six months. On the basis of information derived from consistent photographic recordings of sea-surface patterns and simultaneous underwater pressure records at Woods Hole and Bermuda, it appears possible to derive the average interference pattern of the sea surface from the underwater recordings.

In the latter part of 1946, a quantitative investigation of relationships between sea-surface wave patterns and underwater pressure records was started at the Woods Hole Oceanographic Institution. At that time, an underwater pressure recorder, developed under Navy Contract NObs-2083, was in operation off Cuttyhunk Island; and in November a second pressure recorder was installed off Bermuda. (These underwater pressure recorders were designed and built by A. A. Klebba at the Woods Hole Oceanographic Institution.) To obtain sea-surface data for comparison it was only necessary to observe sea-surface wave heights and periods immediately over the instruments.

The underwater pressure recorder off Cuttyhunk was located at a depth of 75 feet and that off Bermuda at 120 feet. In both cases pressure impulses near the bottom were electrically transmitted to clockwork recorders installed on shore several miles away. Comparative data on the state of the sea immediately overhead were obtained by photographing changes in sea surface against a fixed, floating, graduated pole, using a 16 mm motion picture camera. The graduated pole was anchored near the underwater instrument and synchronization of surface and bottom observations was obtained by exploding a small charge of TNT near the surface while the camera was in operation. This produced a geyser at the surface to be recorded on the photographic film, and a tick on the underwater recorder record. A total of three experiments provide the data for this investigation. Field data for the experiments are outlined in Table 1.

Table 1--Field experimental data, and average height and period of sea surface during observational time

No. Location Date	Photo run	Starting time	Frames exposed	Total time	Average height	Average period
		h m s		h m	ft	sec
1	1	10 58 21	761			
Cuttyhunk	2	11 10 32	759			
June 14, 1946	5	11 48 52	759			
	6	12 01 26	570	01 04	1.19	4.34
2	1	10 33 30	759			
Cuttyhunk	2	10 48 51	759			
June 27, 1946	3	10 52 07	754			
	5	11 11 01	758			
	6	11 21 39	760	00 49	1.42	3.16
5	1	14 53	700			
Bermuda	2	14 57	740			
October 25, 1946	5	15 12	740	00 20	1.5	3.0

The purpose of the investigation was to test (for the two localities concerned) the adequacy of the theory relating surface and bottom pressure fluctuations in the sea. According to hydrodynamic theory, for irrotational wave motion, pressure fluctuations arising from wave height variations of the sea surface should diminish as they are propagated vertically downward. The damping of pressure fluctuations with depth appears to be a function of wave period and depth. At or near the bottom the amplitude of the resulting pressure fluctuation is related to that at the surface as follows:

$$\Delta P_h/\Delta P_s = 1/\cosh kh \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Hence, pressure fluctuations, recorded by means of instruments either suspended in the sea, or resting on the bottom, are not identical with those of the overlying sea surface. The damping phenomenon is selective to the extent that longer period waves, usually obscured at the sea surface, become recognizable in underwater pressure records.

The ratios of bottom to surface pressure fluctuations for the three experiments were computed from direct comparison of individual wave heights of surface and bottom profiles. In Figure 1 they are compared with theoretical values of Equation (1), where it is indicated that the relationship expressed by (1) is not adequate in that pressure fluctuations at the surface computed by means of the relation indicated above are too low.

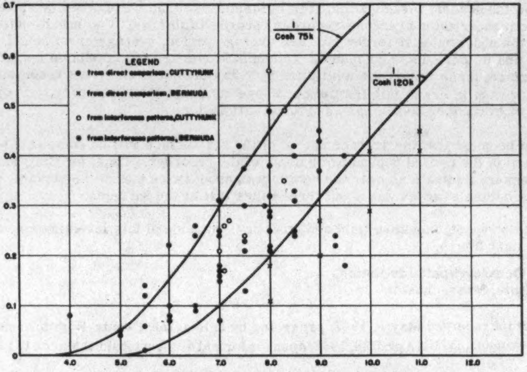

Fig. 1--Ratios of bottom to surface pressure fluctuations ($\Delta H_h/\Delta H_0$) as indicated; theoretical curves for Cuttyhunk (75 foot depth) and Bermuda (120 foot depth), without empirical correction

Table 2--Summary of bottom-surface fluctuation ratios ($\Delta H_h/\Delta H_s$) from interference patterns (IP) and from direct comparison of observations (0), compared with theoretical bottom-surface ratios from Equation (1) ($\Delta P_h/\Delta P_s = 1/\cosh kh$)

Experiment	Range $\Delta P_h/\Delta P_s - \Delta H_h/\Delta H_s$	Average $\Delta P_h/\Delta P_s - \Delta H_h/\Delta H_s$	Average $(\Delta P_h/\Delta P_s)/(\Delta H_h/\Delta H_s)$
1 and 2 (IP)	- 0.13 to + 0.15	0.11	1.31
1 and 2 (0)	- 0.07 to + 0.28	0.12	1.37
5 (IP and 0)	- 0.02 to + 0.20	0.10	1.37
Average		0.11	1.35

Average results for all experiments are given in Table 2, where statistics showing average differences between theoretical, $\Delta P_h/\Delta P_s$, and observed values, $\Delta H_h/\Delta H_s$, and the average ratios of theoretical to computed values, $(\Delta P_h/\Delta P_s)/(\Delta H_h/\Delta H_s)$, are reasonably constant for all experiments. The fact that this should occur for the two locations, 750 miles apart, with different hydrographic characteristics, at bottom depths of 75 and 120 feet, and with observation times four months apart, leads to the conclusion that the average ratios possess empirical significance.

The average ratio of theoretical $\Delta P_h/\Delta P_s$ to computed $\Delta H_h/\Delta H_s$ values was 1.35. Hence, the theoretical relationship, $\Delta P_h/\Delta P_s$, is according to our observations, 1.35 times the observed relationship, $\Delta H_h/\Delta H_s$, or

$$\Delta P_h/\Delta P_s = 1.35\ \Delta H_h/\Delta H_s \ldots\ldots (2)$$

and

$$\Delta H_s = 1.35\ \Delta H_h[1/(\Delta P_h/P_s)] \ldots\ldots (3)$$

Substituting (1) in (3), we have

$$\Delta H_s = 1.35\ \Delta H_h \cosh kh \ldots\ldots (4)$$

as the general equation for estimating sea-surface fluctuations from underwater pressure records. The depth of the pressure recording instrument near the bottom is h. Use of this equation is, for the present, restricted to measurements in the vicinity of Woods Hole and Bermuda.

Based on the present investigation, it is recommended that average sea-surface conditions be computed from underwater pressure-recorder records as follows. Two minute intervals are selected from the underwater recorder tape and average period, average crest height and macimum crest height and its period are computed. To compute average and maximum heights of the overlying sea surface, these values are multiplied by 1.35 times cosh kh. This recommendation, based on equipment in use at this Institution, where the underwater recorder is in operation 20 minutes out of every four hours, has been found satisfactory.

It should be noted that the average period of the sea surface will be somewhat less than the average period of the record depending on depth of the recorder. Thus, for Cuttyhunk the average period of pressure fluctuations near the bottom was about twice that of the surface, whereas at Bermuda, the bottom average was about three times that at the surface.

A complete report, including field and analytical mathods of this investigation, will be published in the near future.

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ACTIVITY OF PARÍCUTIN VOLCANO FROM DECEMBER 1, 1946 TO MARCH 31, 1947

Ray E. Wilcox

(Published by permission of the Director, United States Geological Survey)

A record of the activity of Parícutin Volcano, Michoacán, Mexico, is shown in the diagram of eruptive characteristics, Figure 1, covering the period December 31, 1946 to March 31, 1947, and is supplemented by the maps of the areal extent of the lava flows, Figures 2 and 3. This continues the previous record for the period from September 18 to November 30, 1946 [Trans. Amer. Geophys. Union, v. 28, no. 4, pp. 567-572, 1947], and reference is made to that report for explanatory discussion of the diagram of eruptive characteristics and for general information concerning the methods of investigation.

As shown in Figure 1, the periods of predominantly heavy pyroclastic eruption occurred December 16 to February 14 and March 15 to 28. The periods of greater effusion of lava occurred December 1 to 20 and January 22 to February 25.

During January two segments of the cone slumped, one on the southwest side and the other diametrically opposite on the northeast side. A new lava vent was initiated at the base of each segment almost simultaneously with the slumping. The opening of the new vent at the northeast base marked the first time since the death of the old Zapichu Vent in January, 1944 that lava issued from that side of the cone.

Although a thorough analysis of the observational data has not yet been made, preliminary study does not seem to show a consistent correlation of the activity of Parícutin Volcano with either barometric pressure or tide-producing force during the period December 1, 1946 to March 31, 1947. Complementary activity of the cone and the lava vents, while suggested at times, likewise does not appear to be consistent enough to form a basis for conclusions.

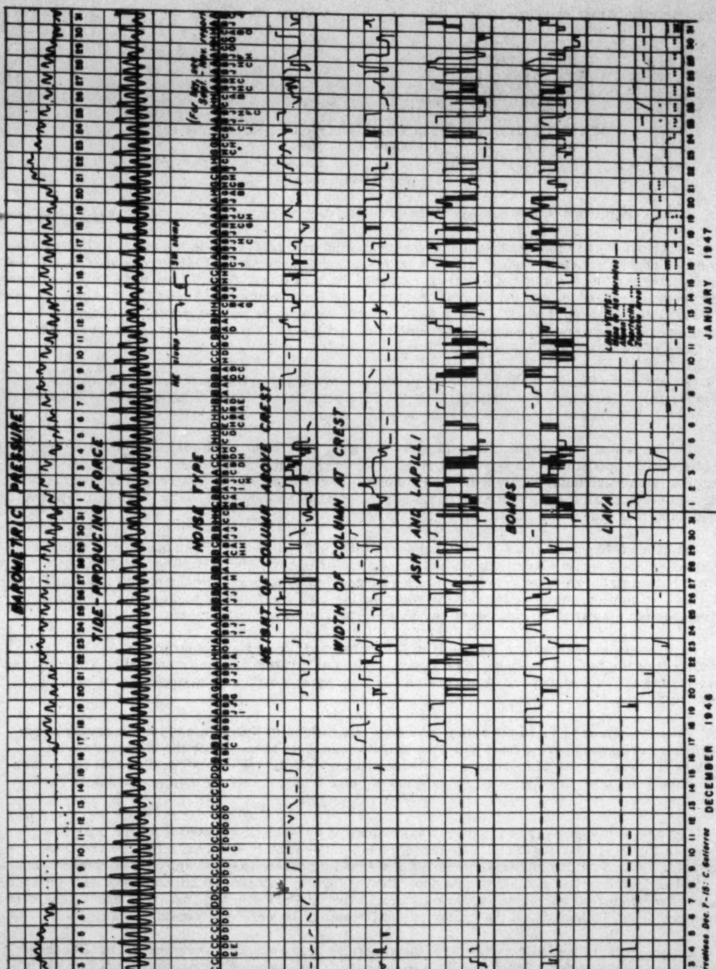
A provisional observatory was built in December and January at Cocjarao Station, 800 m southwest of the base of the cone. The Upper Casitas at Jarátiro Station, menaced by a December lava flow, were moved and rebuilt as one unit in January at a higher point about 300 m west of Jarátiro Station.

From December 7 to 15 the author was on a trip to Jorullo Volcano, and for observations of Parícutin during this period he is indebted to Celedonio Gutiérrez. Since the observations of Gutiérrez are averages of morning and afternoon-evening activities, it is possible that the curves of Figure 1 for this period give an impression of more uniform activity than may actually have been the case.

Activity of the cone--The variations in amounts of pyroclastic erupted from the cone are shown in Figure 1. During the first half of December the activity was characterized by strong explosions with small to moderate amounts of ash and moderate to great amounts of bombs. On December 10 the writer and his companions, then at Jorullo Volcano, 80 km southeast of Parícutin, could hear ponderous explosions apparently originating at Parícutin Volcano. The data of Gutierrez, examined later, indicated that the explosions of December 10 were of exceptional intensity.

A suggestion of periodic variation in the generally heavy eruption occurred during December 19 to 31, in which period a brief decrease in the quantity of pyroclastics occurred at intervals of two to three days, but this apparent periodicity was not carried on into January and February.

On February 15 the heavy eruption of pyroclastics ceased abruptly, and from March 1 to 10 the pyroclastic activity was the weakest yet witnessed by the writer. On March 15 the heavy pyroclastic activity was suddenly resumed without preliminary symptoms and continued generally heavy through the end of the month.


BAROMETRIC PRESSURE
Inches Merc.
22.80
22.70
22.60
22.50
TIDE-PRODUCING FORCE
Milligals
+0.20
+0.10
0
-0.10
-0.20
NOISE TYPE
Predominant
Subordinate
HEIGHT OF COLUMN ABOVE CREST
Meters
3000
2000
1000
0
WIDTH OF COLUMN AT CREST
Meters
300
200
100
0
ASH AND LAPILLI
Quantity
Very Great
Great
Moderate
Small
Zero
BOMBS
LAVA
Observations Dec. 7-15: C. Gutierrez
DECEMBER 1946
JANUARY 1947

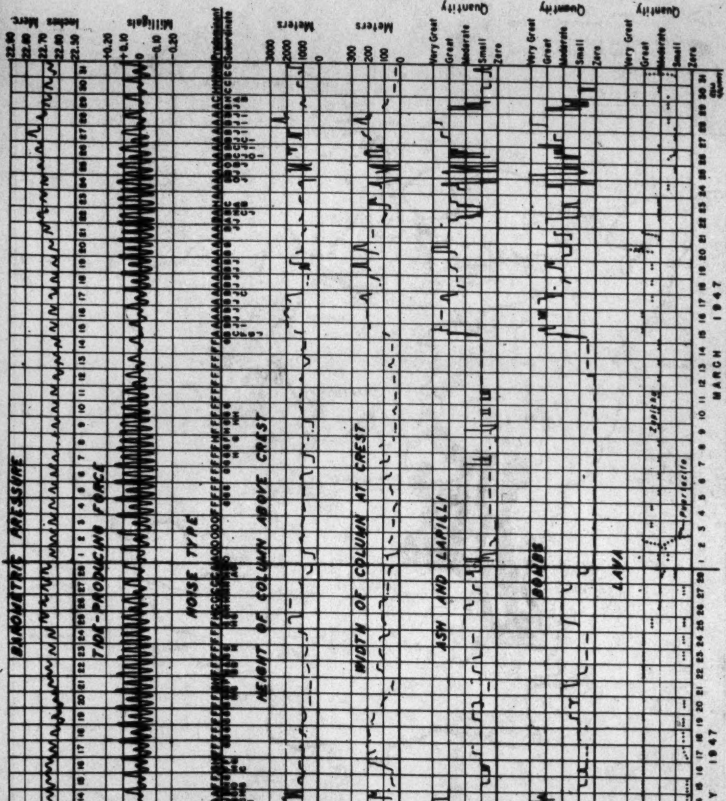


Fig. 1--Eruptive characteristics of Parícutin Volcano from December 1, 1946 to March 31, 1947

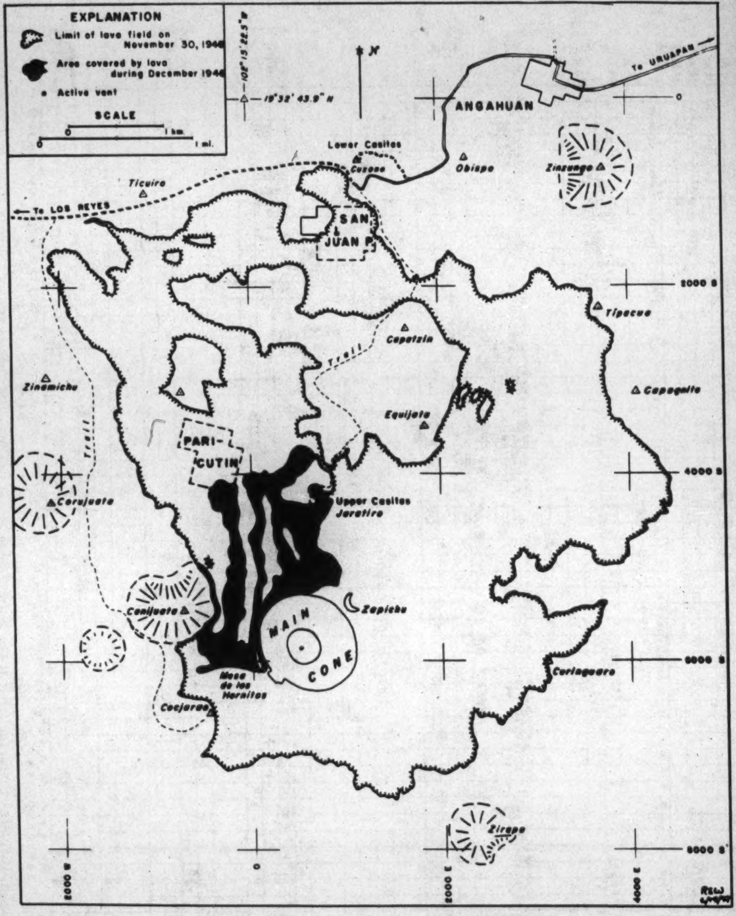

EXPLANATION
Limit of lava field on November 30, 1946
Area covered by lava during December 1946
Active vent
SCALE
0 1 km.
0 1 mi.
102° 15' 22.5" W
19° 32' 43.9" N
N
ANGAHUAN
To URUAPAN
Lower Casitas
Cuzeso
Obispo
Zinzungo
Ticuiro
To LOS REYES
SAN JUAN P.
2000 S
Tipecua
Capatzin
Trail
Zinamicho
Capaquila
Equijata
PARI-CUTIN
4000 S
Corujuata
Upper Casitas
Jaratiro
Trail
Canijuata
Zapichu
MAIN CONE
6000 S
Mesa de los Hornitos
Curinguaro
Cocjarao
Zirapa
8000 S
2000 W
0
2000 E
4000 E
REW

Fig. 2--Lava flows, Parícutin Volcano, December, 1946

Form of the crater and cone--The form of the crater on February 18 was that of a 40 m-deep bowl, in the bottom of which a steep cone-shaped inner crater extended down another 20 m. On the lower part of the southwest wall of the inner crater was a group of closely spaced incandescent jets, from which dense vapors and some incandescent ash and bombs issued with great force. The northeast and southwest rims of the crater were sharp whereas the southeast and northwest rims were crescentic platforms. On February 24 the form of the crater had not changed except the vents were then capped by a perforated rock plug, through which the vapors issued with the same intensity

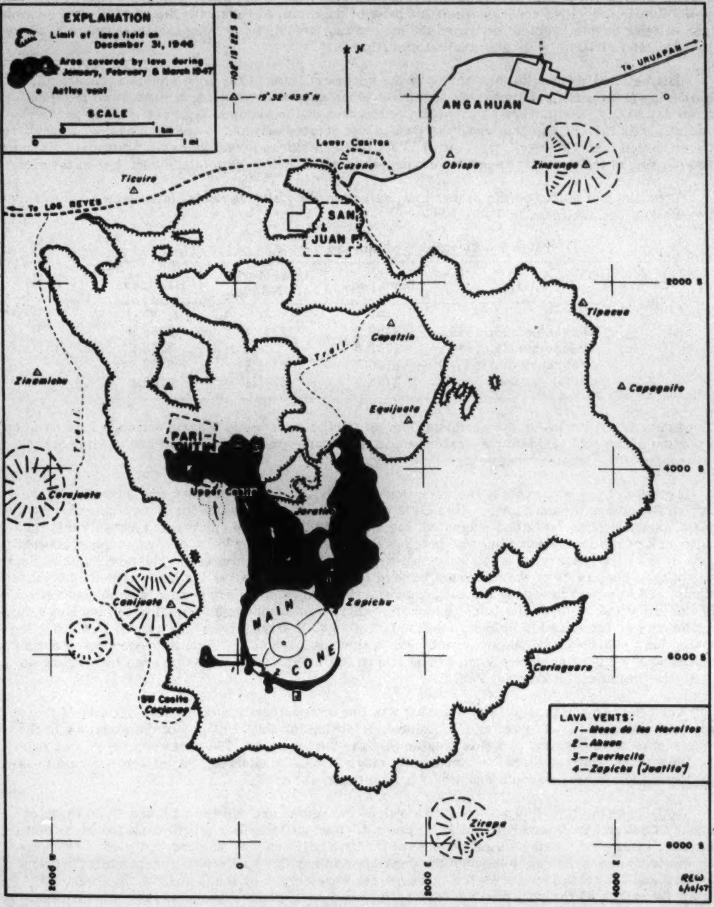

EXPLANATION
Limit of lava field on December 31, 1946
Area covered by lava during January, February & March 1947
Active vent
SCALE
0
1 km
0
1 mi
102° 15' 22.5" W
19° 32' 43.9" N
N
To URUAPAN
ANGAHUAN
Lower Casitas
Cuzeno
Obispo
Zinzungo
Ticuiro
To LOS REYES
SAN JUAN P.
2000 S
Tipacua
Capatzin
Trail
Zinamichu
Capaguito
Equijuata
PARICUTIN
4000 S
Corujuata
Upper Casita
Jaratiro
Trail
Canijuata
Zapichu
MAIN CONE
6000 S
Curinguaro
SW Casita
Cocjaray
LAVA VENTS:
1—Mesa de los Hornitos
2—Ahuan
3—Puertecito
4—Zapichu (Juatita)
Zirapa
8000 S
2000 W
0
2000 E
4000 E
REW
6/10/67

Fig. 3--Lava flows, Parícutin Volcano, January 1 to March 31, 1947

as that of February 18. On March 13, Ariel Hernandez V. reported that the crater still had the form of a cone-within-a-bowl, and much vapor was issuing from cracks in the southwest wall as well as from the vents proper.

The external form of the cone changed markedly during this four-month period. On December 4 two sets of steam cracks converging downward were observed on the southwest flank of the cone in the same positions as the borders of the segment of the cone that had been shoved outward in March, 1946. On January 14 or 15 the segment of the cone between the steam cracks slumped, leaving scarps about 2 m in height extending down the side of the cone, and at the same time the new "Puertecito" lava vent opened at the base of the slumped segment. Slight additional slumping and sagging of this segment occurred during ensuing weeks, depressing the southwest rim an estimated total of 10 m below its original elevation.

Diametrically opposite, a segment of the northeast flank of the cone slumped January 13, the bordering fractures first appearing at the top of the cone and extending farther down the flank from day to day. On January 19 a portion of the base of the slumped segment, exactly in line radially with the old Zapichu vent, was pushed and rotated outward to open the new "Zapichu" vent, (later named the "Noreste" or "Juatito" Vent by the Mexican investigators). Additional slumping and sagging of the northeast segment during January and February totaled about 7 m at the rim.

Elevations of points on the crater rim, determined by alidade shots, (accuracy ± 1.8 m), from Cuzeño Station, are given in Table 1.

Table 1--Elevations of points on the rim of the crater

Date	West peak	Lowest point in NE rim	East peak
	m	m	m
November 28, 1946	2752.3	2741.4	2758.9
December 31, 1946	2752.3	. . .	2758.9
February 28, 1947	2756.7	2734.9	2758.0
April 1, 1947	2756.7	2701.1	2760.1

The figure of 2701.1 m for the northeast rim on April 1 represents a narrow trough formed when a portion of the rim slid into the crater, and it does not represent the amount of downward displacement of the slumped segment.

Activity of the lava vents--The variations in activity of the lava vents are shown in Figure 1. During December the only lava vents active were those of the Mesa de los Hornitos area. By the end of January these vents had stagnated, together with the briefly rejuvenated Ahuan Vent. The main bulk of the lava production was taken over by the Puertecito Vent, opened at the southwest base of the cone January 14 or 15 when that segment of the cone slumped. The new Zapichu Vent was opened January 19 at the northeast base of the cone shortly after the iniation of the northeast slump, and this vent produced a steady but very small amount of lava during January and February. The areas of the Mesa de los Hornitos and the Ahuan vents, although producing no lava flows during February, increased in height an estimated 10 to 20 m during the early part of February, evidently due to slow extrusions and to intrusion below the surface. The main producer in February continued to be the Puertecito Vent, but on March 2 it stagnated at the same time that strong activity was begun at the Zapichu Vent.

Thus the period January 13 to March 2 was one of reorientation of the lava activity of the Volcano. Four vents were active simultaneously during the initial stages of the slumping of the cone segments in January, and it is notable that the Zapichu Vent, 100 m lower in elevation than the Puertecito Vent and therefore apparently more favorably situated, played a minor role in lava production for almost a month and a half before taking the lead.

Activity of the lava flows--The lava flows of December are shown in Figure 2 and those of January through March are combined in Figure 3. During December a flow from the Mesa de los Hornitos vents sent tongues on either side of Jarátiro Hill and only stopped just before reaching the Upper Casitas. During February the persistent fumaroles on the ash-covered hills between Jarátiro and the cone, landmarks for three years, were buried by the flow from the Puertecito Vent. By March 31 the still moving Zapichu flow had exceeded the previous lava limit between Jarátiro and Equijuata and had cut the horse trail leading to the Upper Casitas.

Structurally the flows from the Mesa de los Hornitos, Ahuan and Puertecito vents were similar to the majority of previous Parícutin flows, having a surface of reddish-brown rubble and cinders. The surface of the slow-moving Zapichu flow of January and February, on the other hand, was composed of large dense blocks and extrusions, black in color. After this flow had gained speed in March, the surface was composed of the more usual rubble and cinders.

Weather data--Daily weather observations, recorded at Cuzeño Station as a matter of general interest and possible utility to later investigations, are summarized in Table 2. Data on barometric pressure are given in Figure 1.

Table 2--Climatic summary; December, 1946 to March, 1947

Month	Temperature		Rain		Ash		Minimum relative humidity	Average upper wind direction
	Maximum	Minimum	Total	Maximum	Total	Maximum		
	°C	°C	mm	mm	mm	mm	pct	
December, 1946	26.8	2.0	22.7	10.9	0.0	0.0	. .	SSE
January, 1947	25.2	2.5	67.1	27.2	10.4	2.5	27	SSW
February, 1947	28.2	3.0	0.0	0.0	1.6	0.9	24	WSW
March, 1947	30.9	2.2	2.3	2.3	0.5	0.2	7	WSW

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THORIUM-URANIUM RATIOS IN THE THEORY OF GENESIS OF LEAD ORES

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Abstract--Thorium and uranium determinations by the thoron and radon methods have been made on 19 composite samples from 1500 granitic and intermediate type rocks from various parts of North America. Average Th/U ratios of 3.4 and 4.0 were found for granitic and intermediate type rocks respectively. Such ratios lend no support to Arthur Holmes' theory that lead ores are derived from a source in the substratum below the zone of ordinary magmatic activity. Some regional variations in average Th/U ratios were noted, relatively more uranium being found in the northern part of the continent.

Introduction--During the past decade there has been some controversy over the theory of ore deposits, and some emphasis has been placed on the need of laboratory investigation to supplement findings in the field. In conflicting theories of mode of origin of lead ores, for example, experimental results can help to decide the issue, and by analogy, the conclusions extended to other ores of hydrothermal type. In regard to the source of these ores there are several theories more or less opposed, and in order to clarify the existing problem, the more prominent opinions will be briefly summarized.

Several years ago HOLMES [see "References" at end of paper, 1937, 1938] proposed a theory on the origin of lead ores in which, by an ingenious series of arguments from radioactivity data, he showed that ore lead must have come from a deep-seated source and not from granitic or basaltic magmas as is generally held. He observed that common ore lead always had the same atomic weight of 207.21 ± .01, and that the atomic weights of lead calculated for basic and acidic rock magmas differed from this value and hence showed a variation in their isotopic constitution. He thus concluded that ore leads are derived from a deeper source than basaltic or granitic magmas. KNOPF [1937] while not accepting Holmes' conclusion fully, suggests a possible alternative explanation. There is a high probability that both basic and acidic types of magmas have been differentiated from deeper basaltic magmas and that such differentiation has taken place at or near the beginning of any petrogenic epoch, instead of at the beginning of geologic time. Basaltic magma, accordingly, which is relatively rich in lead, and poor in radioactive minerals, would not generate enough radiogenic lead during the estimated three billion year age of the globe to contaminate the primordial lead appreciably. Hence the atomic weight of such basaltic lead should be close to the normal atomic weight, 207.21. If periodic differentiations take place during the various metallogenic epochs, lead as well as the radioactive elements will be concentrated in the granitic fraction; but, as Knopf argues, the length of such a period is far too short for such accumulation of radiogenic lead as would be necessary to bring about any significant change in the normal value. GRATON [1938], speaking for the majority of geologists, rejects Holmes' theory partially because of his use of inconclusive data and unnecessary assumptions. First of all he questions Holmes' assumption of a uniform atomic weight of primeval lead, and he doubts that mixing of all lead isotopes prior to the consolidation of the Earth actually took place so perfectly as to give a uniform atomic weight of 207.21 in all ore leads. Graton suggests that the limits of error in the radioactive constants and the quantities of thorium, uranium, and lead used in the calculation of atomic weights cast some doubt on the differences upon which the main thesis rests. He points out also that Holmes has, on the same graph, compared present day experimental values of the atomic weight of ore lead with their time of deposition, and atomic weights of rock lead with the various times in the past at which they were calculated. If these values are plotted in the correct perspective, the deviation of the rock leads from the ore leads is not pronounced. Therefore, Graton discounts Holmes' inference of a deep-seated source of lead ores from data which in many respects is inconclusive.

KEEVIL [1938 a, 1944] showed that the weakness of Holmes' theory was in the uncritical averaging of earlier experimental data, and at the same time presented new data for Th/U on which Holmes' calculation of atomic weights of rock lead depended. The new results suggested that the value used by Holmes is probably low, and that the probable average values of Th/U are such as to make the atomic weights of rock lead comparable with those found for ore lead. Keevil also showed that Nier's isotopic analyses of ore leads by the mass spectrometer were in accord with his conclusions from Th/U data, and that, therefore, there is no evident difference indicated between the lead in ore minerals and that present in basaltic and granitic rocks.

The present research was undertaken as an extension of the program to determine the representative thorium and uranium contents and thus the Th/U of various rocks. To increase the scope of the experiments, some 1500 acidic and intermediate rocks from the North American continent were prepared in composite samples. The individual rock samples were geographically grouped and composite samples were made of individual rocks from various sections of North America.

The object of the investigation was to establish with some certainty, the average Th/U of rocks. The determination of this average ratio is of greater importance to the lead ore genesis problem than is the determination of the specific ratio on individual specimens. It was hoped that the procedure followed would give a fairly representative value of the Th/U in granitic and intermediate type rocks.

The Problem--A test of the thesis "that ore lead is a derivative of granitic rock magma" would be to show, by means of the knowledge of the isotopes present in both leads, that the atomic weight of rock lead is essentially the same as that of ore lead. However, such isotopic analysis of rock lead has never been made, owing to the difficulty in handling the infinitesimal concentrations found in rocks. An alternative method is to measure the thorium, uranium, and total lead of the rock, and from these calculate indirectly the isotopic constitution. The Th/U is the necessary factor in obtaining the lead isotope ratio.

$$Pb^{208}/Pb^{206} = (\lambda_{Th}/\lambda_U)(Th/U) = 0.327\ Th/U \ldots\ldots\ldots\ldots \quad (1)$$

The lead ratio can then be applied to the accepted atomic weights of thorium lead and uranium lead and the atomic weight of the radiogenic lead calculated approximately in a manner similar to Holmes.

$$A_r = [(Pb^{208}/Pb^{206})\ A_{Pb}208 + A_{Pb}206]/(1 + Pb^{208}/Pb^{206}) \ldots\ldots\ldots \quad (2)$$

This formula can be used to obtain atomic weight of radiogenic lead today (A_r) and that 2000 million years ago (A'_r), by using the respective Th/U and thus the average atomic weight generated in this period (A''_r) can be estimated. The mass of the radiogenic lead, Pb_r, of this atomic weight can best be calculated from a simplified age equation for old rocks as presented by KEEVIL [1939]

$$t = (\sqrt{1 + 2Kt_1} - 1)/K \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where t = is age of rock in years (applicable up to 2000 million years). (Extension of this formula to 3500 my can be made by applying suitable corrections given in the paper by KEEVIL [1939].)

$$t_1 \text{ (the approximate age in years)} = 7.23 \times 10^9\ Pb_r/[U(1 + 0.327\ Th/U)] \ldots\ldots \quad (4)$$

$$K_{Pb} = [1.953 \times 10^{-10} + 1.624 \times 10^{-11}\ Th/U]/(1 + 0.327\ Th/U) \ldots\ldots\ldots \quad (5)$$

Substituting t_1 and K_{Pb} in (3) and transposing to obtain Pb_r within narrow limits, we have

$$Pb_r = [U(t^2K_{Pb} + 2t)\ (1 + 0.327\ Th/U)]/(14.46 \times 10^9) = \text{(grams/gram of rock)} \ldots \quad (6)$$

K_{Pb} may be worked out from the Th/U or more easily evaluated from the graph [KEEVIL, 1939].

The next step is to calculate the total lead. Although total lead analysis is difficult, careful chemical and photometric procedures have been used with good success as shown by SANDELL and GOLDICH [1943]. From the above information, the atomic weight of rock lead A_{RL} can be calculated as follows:

$$A_{RL} = [Pb_r \cdot A''_r + 207.21\ (Pb_T - Pb_r)]/Pb_T \ldots\ldots\ldots\ldots\ldots \quad (7)$$

where Pb_T is the total lead content, and A''_r is the average atomic weight of radiogenic lead formed in the 3000 million year period.

It is obvious that A_{RL} should come out reasonably close to 207.21 if the above thesis is correct.

Discussion of Thorium-Uranium Ratios--The thorium-uranium ratio for granitic rocks has been shown to be distributed through a range of from 1 to 10. HOLMES [1937] used an average ratio of 1.7 while EVANS and GOODMAN [1941] have quoted a value of 4. KEEVIL [1938a] has shown a probable value of 3 for some 34 analyses of individual acidic and intermediate rocks, but, since all these mean values are based on individual determinations, the resulting value is not necessarily a representative average but a regional one. For instance, of the 34 samples used, ten were from Massachusetts, five from Ontario, and five from Quebec.

Rock magma, from which lead ores were originally derived, must have contained common lead, thorium lead, uranium lead, and thorium and uranium in some fixed ratio just prior to the time of crystalization. During the crystalization period, processes of differentiation set in, which produced local concentrations of these elements. In many cases further processes of secondary enrichment tended to produce local concentrations throughout geological time. Either or both of these processes have acted on most rock constituents to a greater or less extent. For this reason many determinations must be made to eliminate statistical variations due to local concentrations. Hence for adequate analysis of the Th/U and the total lead contents, the tests must be made over an area large enough to represent all zones of the Earth's crust.

Preparation of the Samples--The scope of this research has been confined mainly to North America from which most of the samples were taken during part of a broad study by Keevil on the distribution of radioactivity in North American rocks. To test the possibility of appreciable regional variation of thorium and uranium in the Earth's crust, the continental samples were divided into nine groups (see Table 1 and Figure 1). Each group was then subdivided into granitic (series A) and intermediate series (series B). Composite samples of equal weights of each rock of the various sections were made up, resulting in an "A" and a "B" sample for each of the nine regions. A set of 30 samples from various parts of Europe, Asia, and Africa was also made up (Group 1A). The samples were slowly rotated in a mechanical tumbler for several days to give a uniform mixture. From these group samples, a small amount was removed for measurement of a group activity (A_e). Several determinations were made on each group to insure a representative average value

Table 1--Geographic location of the sampling groups

Group	Location
1	All outside North America
2	Ontario and Quebec
3	Northeast Coast--Baffinland, Greenland, Labrador, Newfoundland, Nova Scotia, New Brunswick, Maine, New Hampshire, Vermont, Massachusetts, Connecticut, and Rhode Island
4	Eastern States--Michigan, Indiana, Ohio, New York, Pennsylvania, New Jersey, Kentucky, Tennessee, Virginia, West Virginia, Delaware, Maryland, North Carolina, South Carolina, Georgia, Florida, Alabama, and Mississippi
5	Central States--Wisconsin, Minnesota, Nebraska, Missouri, Louisiana, Iowa, Illinois, Kansas, Arkansas, Oklahoma, North Dakota, and South Dakota
6	Southwestern States--Texas, New Mexico, and Arizona. Mexico included in this group
7	Western States--California, Oregon, and Washington
8	Rocky Mountain States--Montana, Idaho, Wyoming, Nevada, Colorado, and Utah
9	Central Canada--Manitoba, Alberta, Saskatchewan, Yukon, and Northwest Territories
10	West Coast--British Columbia and Alaska

For the thorium and uranium analyses, 2.5 to 10 grams of the group samples were fused with the Na_2CO_3 with $Ba(OH)_2$ as a carrier. The whole was then brought into solution with HCl. In the procedure formerly employed the thorium chain was frequently broken. Care was taken in this instance not to break the chain. In this way, repeat analysis of thorium can be performed at any time after the initial preparation. In several cases NaCl was precipitated from the solution on acidification. The NaCl was removed by filtration and then given a thorough washing with absolute alcohol to insure no loss or break in the thorium chain. Such a method was found quite satisfactory for the removal of excess salt, since the alcohol, besides being radioactively inert and producing negligible contamination, dissolves a minimum of salt. The resulting solution was then used for both the thorium and radium analyses.

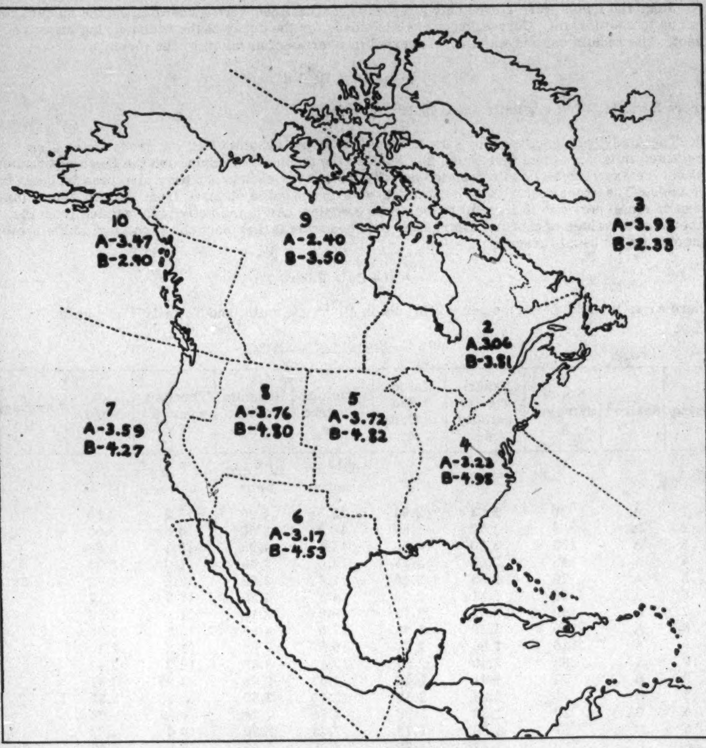

Fig. 1--Sketch map showing Th/U values

Thorium and Uranium Analyses--The thorium analyses were made by the constant streaming method used by URRY [1936] and improved by KEEVIL [1938b]. The radioactive thoron gas liberated from the rock solution by agitation with nitrogen was allowed to pass through an ionization chamber at a constant rate. The alpha particle pulses were amplified by a direct current amplifier employing a G. E. FP-54 pliotron tube and galvanometer swings due to alpha ray pulses recorded on photographic records.

The radium analyses were made by a similar apparatus except that a static arrangement was used because of the longer half-life of radon gas. The rock solutions were stored in 500 cc boiling flask fitted with a fine seal-off tip and nitrogen bubbling tube. The radon was removed by heating the solution to about 100 degrees C and simultaneously bubbling radioactively inert nitrogen through it. After evacuation of the sample bulb, the line was opened to the bulb by breaking the seal-off tip which is enclosed in a heavy rubber coupling. In order to remove water from the gas, the radon-bearing nitrogen was allowed to pass through a reflux condenser and phosphorus pentoxides drying tube, en route to the ionization chamber.

Since the flasks were stored only a few days, corrections were made to bring the radium content up to equilibrium. Corrections were also made for the decay of the radon during measurement. The radium content was then converted into terms of uranium by the formula

$$U = 2.84 \times 10^6 \, Ra$$

where Ra is in 10^{-12} g/g units and U in 10^{-6} g/g units.

The Analytical Results--For sake of comparison, the results of all the groups have been presented in tabular form (see Table 2). Besides the thorium, uranium, and the thorium-uranium ratios, the experimental and calculated activity indices for each group have also been included in the table. The experimental activity, (Ae), is an average value obtained from several determinations on small portions (0.1 gram) of the group samples. Ar is the activity calculated from the experimental values of thorium and radium obtained from larger portions (3 to 10 g) of the same samples by the usual formula.

$$Ar = 0.104 \, Ra + 0.0886 \, Th.$$

where Ar is in alpha particles per mg/hr, Ra in 10^{-12} g/g units, and Th in 10^{-6} g/g units.

Table 2--Results of analyses

Group	Series[a]	No. of samples N	Experimental activity Ae	Calculated activity Ar	Radium content Ra	Uranium content U	Thorium content Th	Th/U	Average Th/U
					10^{-13} g/g units	10^{-6} g/g units	10^{-6} g/g units		
1	A	30	3.03	2.94	15.3	4.35	15.2	3.50	
2	A	396	1.72	1.85	10.2	2.90	8.89	3.06	
3	A	123	3.20	3.58	17.5	4.98	19.8	3.98	
4	A	143	2.46	2.23	12.0	3.40	11.0	3.23	
5	A	76	2.55	2.45	12.4	3.52	13.1	3.72	3.39
6	A	50	3.11	2.72	14.8	4.20	13.3	3.17	
7	A	52	2.01	2.12	10.9	3.10	11.1	3.59	
8	A	199	3.39	3.48	17.5	4.98	18.7	3.76	
9	A	126	2.68	2.71	16.5	4.68	11.2	2.40	
10	A	92	2.40	2.37	12.4	3.52	12.2	3.47	
2	B	72	1.41	1.48	7.37	2.09	7.95	3.81	
3	B	31	2.25	2.17	13.4	3.80	8.86	2.33	
4	B	20	1.32	1.06	4.56	1.34	6.58	4.98	
5	B	17	1.89	1.75	7.73	2.20	10.6	4.82	
6	B	10	1.87	1.95	8.85	2.52	11.4	4.53	3.98
7	B	23	1.97	1.92	9.05	2.57	11.0	4.27	
8	B	52	2.35	2.14	9.55	2.72	13.0	4.80	
9	B	23	2.63	2.49	13.0	3.70	12.9	3.50	
10	B	49	1.70	1.59	9.00	2.56	7.42	2.90	

[a] Series A, granitic rocks; series B, intermediate rocks

Theoretically there should be very close agreement between values of Ae and Ar. However, the apparent disagreement in several cases is not too serious when one considers the highly concentrated nature of the radioactivity in several of the accessory minerals. As has been pointed out by KEEVIL [1943] and KEEVIL, LARSEN, and WANK [1944], one such highly radioactive particle could conceivably cause such a discrepancy. The average Th/U for granitic rocks is about 3.4 whereas that of intermediate rocks is about 4.0.

Discussion of Results--On the whole the average thorium-uranium ratios support the averages obtained by Keevil on individual samples. As expected, the content of radioactive minerals is higher in the granitic types than in the intermediate type rocks but Th/U is 17 per cent higher in the latter type. This would seem to indicate that acidic magmas, though more radioactive than the intermediate rocks, retain more uranium than thorium. Average values of thorium and uranium contents of both groups show that the thorium content of the acid group is about 33 per cent higher and uranium content about 47 per cent higher than in the intermediate group. This suggests that about 14 per cent more uranium has been retained in acidic magmas, provided we assume that such acidic magmas were originally differentiated from basic magmas. However, it is conceivable that this increase could be due to a cause other than differentiation.

An interesting observation has been made of the regional distribution of thorium and uranium. The ratios are plotted on Figure 1. It will be noticed that the values in Canada and Alaska are lower than those in the United States. A calculation of the average thorium and uranium contents of the United States and Canadian Shield groups is given in Table 3. The decreased ratios toward the northern regions are due to an increase of uranium and a decrease in thorium.

Table 3--Average thorium and uranium contents

Element	Series	Canadian Region Groups 2, 3, 9, and 10	United States Region Groups 4, 5, 6, 7, and 8	Ratio Canadian/United States
Uranium	A	4.02	3.84	1.05
Uranium	B	3.03	2.27	1.34
Thorium	A	13.1	13.5	0.97
Thorium	B	9.28	10.5	0.88
Th/U	A	3.27	3.52	0.93
Th/U	B	3.06	4.63	0.66

Little significance is attached to the small variations in granitic rocks shown in the table, but the rather large variations, especially in the uranium content, evident in the intermediate type rock may be of some importance. This suggests a connection between the increase in uranium and the existence of the radioactive province centered around Great Bear Lake.

In regard to the problem of lead ore genesis it can be said that these results confirm the previous arguments against a deep-seated source of lead ores. Undoubtedly some magmas will have thorium-uranium ratios of the order of 2.5, but in the main, even for most acidic rocks, the ratio will be above 3.0, a value which will give an atomic weight well within the range of the isotope analyses of ore lead (207.175 to 207.236). It is the authors' opinion that these results and those of previous workers show no reason to assume, as Holmes does, a source of ore lead other than that of ordinary rocks or rock magmas.

Summary and Conclusions--(1) The analyses of group samples of over 1500 igneous rocks indicate an average value for the thorium-uranium ratio of 3.4 for granitic rocks and 4.0 for intermediate rocks. Such values would give an atomic weight of rock lead approximately that of ore lead and thus do not support Holmes' theory that lead ore deposits have a deep-seated source. (2) Experimental data indicate that the acidic magmas, while known to contain quantitatively more uranium and thorium than basic magmas, retain relatively more uranium than thorium than do intermediate magmas in the same region. (3) There is also some evidence that a regional distribution of thorium and uranium exists on the North American continent. The thorium-uranium ratios of the Canadian Shield are lower than in the United States. There is roughly a 20 per cent higher uranium content in the intermediate rocks of the Canadian Shield, but this difference is not shown by the results in granitic composite samples.

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HYDROLOGIC DATA FOR HIGHWAY DESIGN

R. Robinson Rowe

In modern design of highways, increasing use is being made of hydrologic data. This is due in part to the higher standards of highways, requiring such large investments in embankments and structures that we can afford more study of climatic forces to be resisted. It is also true that more hydrologic data are being recorded each year and that these data are being published in more convenient form.

However, there is still a wide gap between supply and demand for hydrologic data. Granted that this supply will depend upon appropriations for basic observations, the purpose of this paper is to suggest publication of the compiled data in a form which will be more useful in highway design. To introduce the suggestions it will be of interest to review our present practice in application of hydrology and demonstrate an improvement in practice if data were published in the suggested forms.

Design principles--Whenever data are adequate, we prefer to design highway facilities to be secure during floods of certain frequency. Otherwise we are forced to design for a historic flood of unknown frequency.

The expression "of certain frequency" does not mean that a uniform frequency would be used for all design. Where failure in flood means great loss of life or property, the design frequency may properly be 100 years or more. At the other extreme, for detours and temporary routes, a frequency of five years or less may be just as proper. In short, design frequency is a function of consequences of failure.

Stream-flow data--In designing large bridges, we usually attempt to compute the 30-year flood crest, that is, the momentary peak discharge likely to be equalled or exceeded on the average once in 30 years. If stream-flow records are not available for the stream, we make use of records for similar streams and adjust for differences in drainage area, climate, and topography.

Of 3400 California state bridges over streams, 1550 are classed as large bridges, crossing 1200 independent waterways. Of these waterways, only 150 are measured for publication of stream-flow data.

In order to compile frequency data, it is necessary to refer to annual Water-Supply Papers of the United States Geological Survey for each year of record. Complete sets of these papers are scarce, so that the research is often expensive.

In the United States Geological Survey's Surface-Water reports for 1939 an attempt was made to collect such data in a "Yearly-Discharge Summary," but the annual maxima tabulated in the summary are maximum mean daily discharges instead of momentary peaks.

In Geological Survey Water-Supply Paper 771 it was shown that maximum mean flow for 24 hours may be as great as 1.8 times and momentary peak 17.6 times the maximum mean daily discharge, demonstrating that the latter was an unsatisfactory base for floodway design. That Water-Supply Paper made a splendid start by compiling the peak discharges of many streams.

Such a study can be made only by study of the original hydrographs, because published records prior to 1938 listed only the greatest peak of each year. When two independent damaging floods occur in the same year, both should be considered in frequency studies.

In Water-Supply Paper 771, a base discharge was determined for each gaging station and all peaks in excess of the base were published. It is suggested that this procedure be adopted for all gaging stations, that future Water-Supply Papers publish all peaks in excess of the base. Later, when funds and time permit, old records should be reviewed to extend to all gaging stations summaries like those of Table 3 in Water-Supply Paper 771.

It is also suggested that the Water-Supply Papers could render a valuable service by listing stream-gaging stations maintained by other agencies, so that the one volume, if it could not publish all stream-flow records, would at least be an index to all records and all sources of flood-discharge data, regardless of accuracy.

Precipitation data--The smaller the drainage basin, the more we rely on precipitation-intensity frequency for estimation of design floods. Small bridges are usually designed for 30-year frequency and basins of one to ten square miles, from which flood peaks concentrate in 20 to 200 minutes. Culverts serve a smaller overlapping field, basins of five to 3000 acres concentrating in five to 100 minutes. Since failure of a culvert usually means loss of much embankment, we design for a frequency of 100 years.

Still smaller basins are involved for surface drainage of the highway itself. The most important of many problems in this field is the underpass served by pumps. Economy of design of pump facilities involves a balance between pump capacity and storage in a sump, so that critical concentration times may vary from three to 15 minutes.

We have, therefore, many important design problems for which we desire precipitation-intensity frequency for durations of less than an hour. The wide variation and meagerness of data for California was noted by Yarnell [see "References" at end of paper, YARNELL, 1935], who published short-period intensity frequency for all of the other states. It was true then and is true now that precipitation-intensity frequency for short periods cannot be determined in California from published data, except for a very few stations.

In 1940 we found ten-year records for only 14 stations, of which 11 were within a few miles of the Pacific and 13 were below the 300-foot contour. But there were 196 precipitation recorders in operation at an average elevation of 2118 feet, so that we anticipated a fairly good measure of frequency throughout the state by 1950. The program of observation has expanded until there are 260 recorders for which hourly precipitation is published regularly [ANONYMOUS, 1946].

In the face of this tremendous expansion of observation and publication of precipitation data, it would be very unfair to criticize the results. Certainly the meteorologists are to be commended for their achievement in organizing and financing the program. Let us say, then, that suggestions made in this paper are not critical of the past but hopeful for the future.

The first suggestion is that records of unusually intense precipitation be published by five-minute periods. The form of publication could be similar to that used by the United States Weather Bureau for "excessive precipitation," for which the base was established at $P_e = 0.01\ (Tm + 20)$, that is, precipitation was considered excessive if the fall in hundredths of an inch exceeded the time in minutes plus 20.

As a second suggestion, it is proposed that the base for "excessive precipitation" be changed so that the volume of data to be compiled and published will not be much greater than that actually needed for computation of frequencies. The present base gives too many data for 15-30-minute bursts and too little for five-minute bursts. It gives fewer data for north coastal stations than for the rest of the State of California. Hence the suggestion implies several non-linear definitions of excessive precipitation appropriate to the several climatic regions of the State.

To illustrate the point, Table 1 compares for periods up to 120 minutes the present definition and definitions which might be appropriate for San José on the north coast and Fresno in the Central Valley of California. Definitions for mountain and desert areas may be distinctly different.

As a third suggestion, it is hoped that storms of unusual intensity will be reported with collateral detail as a regular procedure. This was done in notable fashion for the storm of January 19-24, 1943. In many instances the personal notes of observers added greatly to the value of data from non-recording stations. In such reports it will be possible to estimate intensity for periods when the recorder is not in operation.

There is a good example of this opportunity in the storm of October 5-7, 1945, in the southern Sierras. An area 200 miles long by 50 miles wide received an inch of rain or more. Although there were eight recorders in the area, only one observed an intensity greater than 0.76 inch per hour, but the storm caused the deaths of 11 persons and flood damage of about $1,000,000. The losses occurred because of local cloudbursts five to 20 miles in diameter. Only one of these was caught by a recorder and there (Tehachapi) the clock stopped. The published record shows a fall of 3.17 inches in 15 hours but the observer recalled later that the storm passed in two hours. This comment and interview of others who witnessed the storm would have filled in much of the record lost by failure of the clock. For instance at Cinco, where there are no gages, a man timed one cloudburst at 20 minutes, then measured 2.5 inches of water in a flat can which was empty before the storm. Even if this unofficial observation is 50 per cent in error in depth or duration, it is more valuable than the bare official report from Tehachapi.

Table 1--Comparison of present and appropriate definitions of precipitation for San José and Fresno, California

Period	Excessive precipitation		
	Current definition	Appropriate definitions for	
		San José	Fresno
min	in	in	in
0	0.20	0.00	0.00
5	0.25	0.12	0.18
10	0.30	0.20	0.30
15	0.35	0.26	0.38
20	0.40	0.32	0.45
30	0.50	0.40	0.54
40	0.60	0.48	0.61
60	0.80	0.58	0.70
90	1.10	0.70	0.81
120	1.40	0.80	0.90

As a fourth and final suggestion, why not establish trap gages in regions subject to cloudbursts. Although such storms occur frequently in these regions, the area covered by each storm is small and a particular spot may not be drenched very often. So instead of a continuous recorder, a gage might be designed to start on a hard rain just as the trap seismograph starts with the first earthquake shock. Weight of catchment could be used to pull the trigger and drive the clock. When potential energy of the catchment was used, the clock would stop. To avoid recording moderate intensities, another tube could be set to by-pass some catchment around the clock. In that case, the record would show excess intensity above the by-pass rate. Such gages could be remotely located, as inspection once a year would be sufficient.

Summary--Summarizing, this paper has pointed to practical applications of hydrology to highway design. In order that these applications can take full advantage of new data being collected, suggestions have been made as to form of publication. These suggestions are not recommendations, for it is realized that form of publication must be such as to serve many other users. The real objective is to obtain publication of data suitable for frequency studies for short-period intensities.

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SUSPENDED-MATTER SAMPLING AND CURRENT OBSERVATIONS IN THE VICINITY OF HUNTERS POINT, SAN FRANCISCO BAY

J. A. Putnam, K. J. Bermel, and J. W. Johnson

In connection with hydraulic model studies of proposed structures at Hunters Point in San Francisco Bay, extensive observations were made on suspended-matter concentration, current velocity and direction, and bottom material composition. Because this information may be of value in connection with future investigations on harbor installations, sewage disposal plants, and other works, the data are summarized as a matter of record.

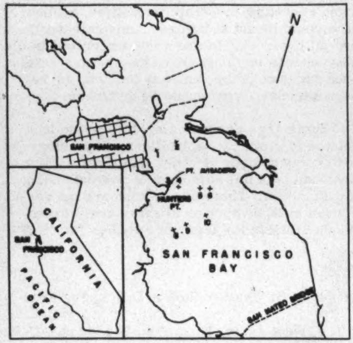

Fig. 1--Map of San Francisco Bay showing location of current and sediment sampling station

The various observations were taken over approximately a 92-hour period on April 14-18, 1945. As mentioned above, these observations included suspended matter and bottom sampling, current velocities and directions, as well as a continuous record of the stage of tide, by a tide machine, at Point Avisadero (see Fig. 1). Shown on Figure 1 are the locations of the nine stations at which continuous observations were taken. Eight of the stations were anchored boats, and one was on shore at Point Avisadero. The boats were provided and operated by the United States Coast Guard Reserve. Observations aboard boats were made by personnel provided by the United States Navy, Twelfth Naval District. Equipment and supervision for the current observations were provided by the United States Coast and Geodetic Survey.

Water samples for obtaining suspended-matter concentrations were collected at each station approximately every six hours during the period of observation. At a particular time, a sample was taken one foot above the bottom, another, one-fourth of the depth from the bottom, and a third, one foot below the surface. All samples were collected in weighted pint milk bottles, the procedure being to lower a bottle to the desired depth by a graduated rope and then remove a 1/2 inch diameter stopper by jerking a second line attached to the stopper.

Current velocities were obtained throughout the vertical at each station by means of Price current meters which are used by the United States Coast and Geodetic Survey in connection with various current surveys. Current velocities were measured at 0.2, 0.5, and 0.8 depth and one foot above the bottom at one-hour intervals throughout the period of observation. Surface velocities were determined by means of current poles. (In this method the velocity is calculated by noting the interval of time for a pole, weighted to float vertically, to drift a known distance away from the boat.) Surface-current directions also were obtained at frequent intervals by taking "fixes" from a boat which closely followed freely-drifting surface floats.

Samples for obtaining the composition of bottom material were collected as follows: Where the bottom material was hard, samples were obtained from the anchor spurs. Where the bottom was of soft material, a bucket was dragged along the bottom, and enough material was collected to fill a quart jar.

Suspended-matter data--Approximately 250 water samples were taken during the period of observation. These samples, of approximately a pint each, were analyzed in the Engineering Materials Laboratory of the University of California for the following information: (1) Concentration

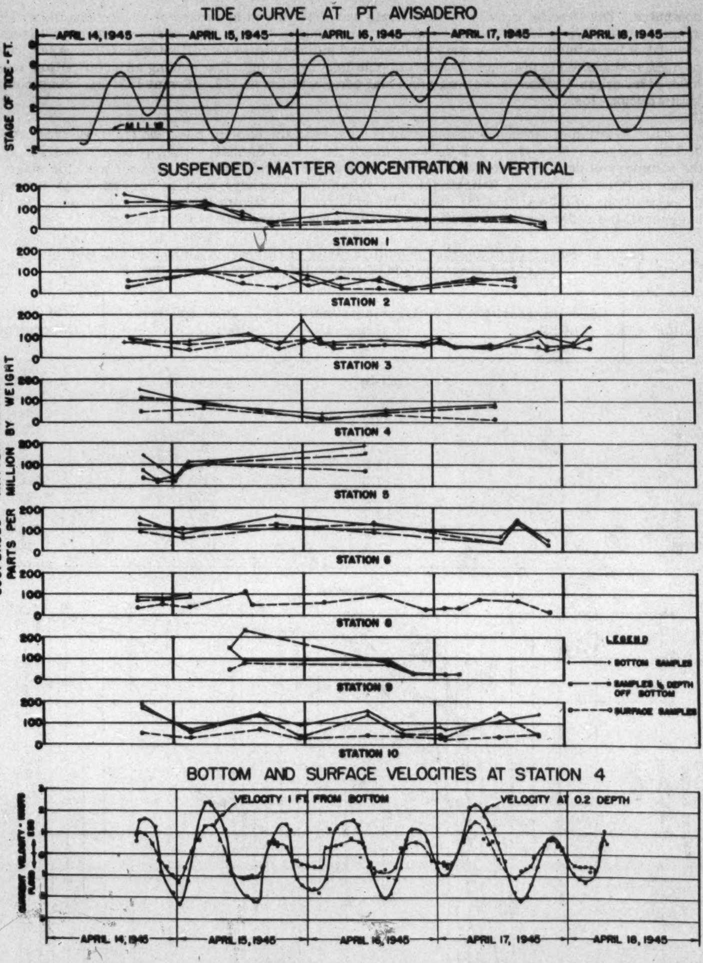

Fig. 2--Variation of suspended-matter concentration with depth and stage of tide

of a filterable sediment; (2) specific gravity of the filtrate; and (3) organic content and ignition loss of sediments of certain composite samples. The procedures followed in these analyses were briefly as follows: The samples were filtered through a 20-ml, fritted, glass filtering crucible of medium porosity. The crucible and contents were oven dried for one hour at 230°F. By weighing the filtrate and measuring its volume, the concentration of the filterable sediment was computed. The specific gravity of the filtrate was determined by means of a hydrometer having a range from 0.9990 to 1.0300 with a least-scale reading of 0.0010. The sediments removed from each filtering crucible by hot water, washing, and policement were collected on filter paper, composited, and ignited in platinum crucibles. The loss occurring after ignition at 1000° F was considered as organic content, and that occurring after ignition at 1825° F was considered as total ignition loss.

The variation of the suspended-matter content near the bottom, one-quarter depth from the bottom, and near the surface, for the duration of the period of observation, is best visualized by the summary of data presented in Figure 2. The upper portion of this diagram shows the stage of tide at Point Avisadero. Beneath this are shown the suspended-matter concentrations at the three positions in the vertical for each of the nine stations. From Figure 2 it can be seen that, in general, the sediment concentration is larger at the bottom than at the surface.

Table 1--Summary of average specific gravity of filtrate, organic content, ignition loss, and concentration of suspended-matter at each station

Station	Specific gravity of filtrate at 68° F	Organic content of sediment	Total ignition loss at 1850° F	Sediment Concentration
		pct by wt	pct by wt	p pm by wt
1	1.019	28.0	30.0	61
2	1.019	12.8	13.8	63
3	1.019	17.5	18.5	76
4	1.019	14.6	16.4	69
5	0.018	12.0	13.2	118
6	1.018	11.9	13.5	95
8	1.019	12.7	14.7	76
9	1.019	13.5	15.5	70
10	1.019	14.2	15.8	79

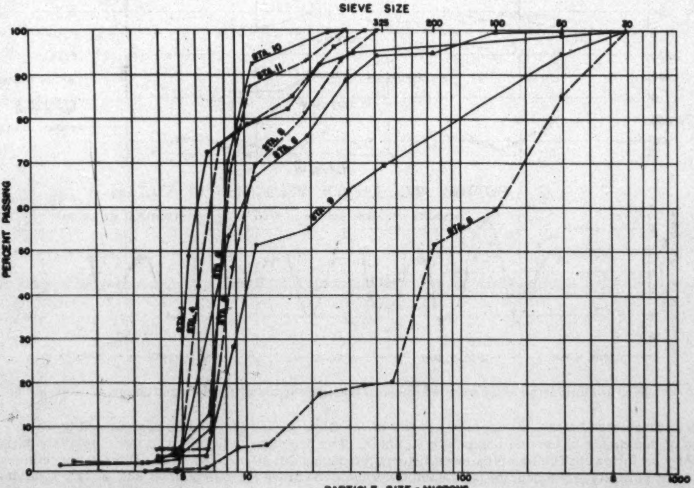

Fig. 3--Mechanical analysis of bottom samples at various current stations

The data on specific gravity of filtrate, organic content of sediment, and total ignition loss are summarized as average values for each station in Table 1. Also included in the Table is an average sediment concentration for each station, the average being a grand average of all samples taken at each station.

Bottom composition--The bottom-material samples collected at each observation station were analyzed for particle size by means of settling velocities. The ASTM method D-422-39 was used in the analysis with the following changes. The sample was tested in the condition taken by first removing the shell fragments by passing the wet sample through a 30 mesh sieve. To avoid drying and subsequent grinding, the dry sample weight of material was detremined after the test, instead of before. The material was allowed to settle in sea water, the latter being the composited filtrates from the suspended-matter samples. At the conclusion of settling tests, the mud suspensions also were wet-screened to determine their size analysis on the Nos. 50, 100, 200, and 325 sieves.

The size analysis curves for the bottom samples taken at the various stations are shown in Figure 3. A summary of the specific gravity of dried material, organic content, and total ignition loss for the various samples is given in Table 2. A complete bottom sample for Station 2 was unobtainable with the method used. A partial sample indicates that this area consists of compacted blue clay and great quantities of shell.

Table 2--Analysis of bottom samples, San Francisco Bay

Station	Specific gravity of dried material	Organic content ignition at 1000° F	Total ignition loss at 1850° F
		pct by wt	pct by wt
1	2.59	7.05	9.35
4	2.44	7.21	8.91
5	2.55	2.47	3.24
6	2.50	7.02	10.05
8	2.49	5.87	9.41
9	2.50	6.80	8.93
10	2.39	8.77	10.56
11	2.42	8.31	10.71

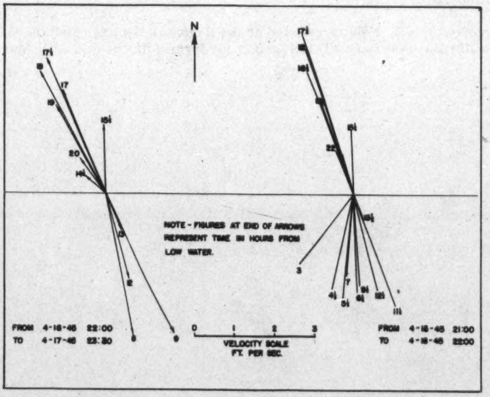

Fig. 4--Surface current roses for Station 4

Current measurements--At all stations, velocity measurements were made at 0.2, 0.5, and 0.8 depth below the surface and one foot above the bottom by Price current meters. At each of these stations, current directions of the surface were observed by current pole or by measuring the direction of the path of a free float in the immediate vicinity of the station. The directions obtained by current pole are averages of a number of observations.

The data on current velocities have been summarized for each station as illustrated in Figure 2 for Station 4. The current velocity for two positions (one foot above bottom and at 0.2 depth) has been plotted against time with the direction of flow (ebb or flood) indicated.

The observations of current direction at each station have been summarized in the form of "current roses" which show the current magnitude as well as direction for each complete tidal cycle. A typical example is shown for Station 4 in Figure 4. For more detailed information on current velocities and direction in the shoal area to the south of Hunters Point, observations were made during a complete tidal cycle on October 11, 1945. These measurements were obtained by releasing free floats and "cutting in" their location at frequent time intervals by two transits on shore. The paths of the floats were then plotted from which the current direction at each hour was obtained by the tangent to the path. The velocity at each of these hour intervals was obtained by plotting distance along the path against time of observation; the tangent to this curve at each hour gives the velocity of the float. A map to show current velocity and direction was then made for each hour during the tidal cycle.

Conclusions--Previous observations in San Francisco Bay to the north of the San Francisco-Oakland Bay Bridge have been made on current velocities and directions, turbidity and temperature of Bay waters, and a limited number of bottom material analyses [see "Reference" at end of paper, HYDE, GRAY, and RAWN, 1941]. The data summarized in this paper give information, somewhat similar in character, for the adjacent area of the Bay to the south. A complete summary of all data cannot be presented herein; however, these data are available in the files of the Fluid Mechanics Laboratory of the University of California for the use of interested parties.

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TRANSVERSE DISTRIBUTION OF SUSPENDED SEDIMENT BELOW RIVER CONFLUENCES

Albert E. Coldwell

Abstract--At the confluences of the Arkansas River with three of its important tributaries near Tulsa and Muskogee, Oklahoma, the water of each stream retains its identity as far as suspended load is concerned for a considerable distance downstream from the confluence. Presented here are selected observations of suspended sediment concentration, illustrating its transverse distribution for various rates of discharge.

The phenomenon of streams of muddy and clear water flowing side by side for many miles before mixing has been referred to in literature about density currents and stratified flow [see "References" at end of paper, BELL, 1942; GROVER and HOWARD, 1938]. A classic example of this in the United States is the confluence of the Missouri and Mississippi Rivers when the former is in flood [SIMPICH, 1945]. Other cases of the junction of various colored streams of water have been noticed in Arkansas, where streams of clear, blue water draining the foothills of the Ozark Mountains were in striking contrast to the reddish-brown flood-swollen Arkansas River into which they emptied.

In the course of investigations by the United States Corps of Engineers into the amount of suspended sediment load carried by the Arkansas River in Oklahoma, quantitative measurements of the characteristics of parallel currents became available. Samples of water and its suspended sediment were obtained from the main stem of the Arkansas River at Tulsa and Muskogee, Oklahoma (see Fig. 1). Tulsa is about 18 river miles below the point at which the Cimarron River, a heavily-laden sediment stream, enters the Arkansas River from the right. Muskogee is about 65 river miles below Tulsa and is about two river miles below where the Verdigris and Grand Rivers, both comparatively clear streams, enter the Arkansas River from the left.

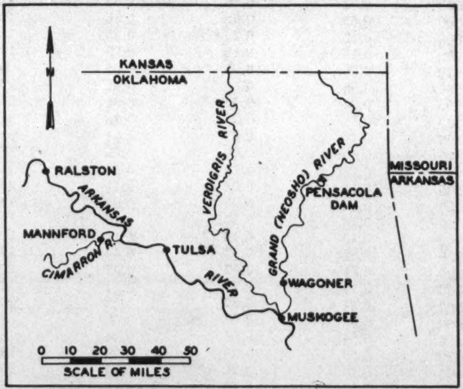

Fig. 1--Portion of the Arkansas River watershed.

For similar discharges the concentration of suspended sediment of the Arkansas River above the mouth of the Cimarron River is usually less than that of the Cimarron River, the average being about 0.2 per cent by weight for the former and about 0.7 per cent for the latter. Much of the area drained by the Cimarron River is known as the "Red Plains Area," [DANIEL, ELWELL, and COX, 1943] which causes runoff water to be noticeably red in color, as compared with a grayish-brown color of water in the main stem of the Arkansas above the confluence of the two streams.

Table 1--Concentration of suspended sediment samples taken at various points in cross-section of Arkansas River, Twenty-First Street Bridge, Tulsa, Oklahoma, Mannford discharges less than 3000 cfs

Date	Discharge at Tulsa	Suspended sediment concentration by weight			Average daily discharge on previous day at upstream stations	
		Left bank sample	Mid-stream sample	Right bank sample	Mannford (Cimarron River)	Ralston (Arkansas River)
	cfs	pct	pct	pct	cfs	cfs
5-23-40	12,700	0.45	0.79	1.06	2120	9560
7- 8-40	10,300	0.43	0.52	0.63	1490	7550
4-24-41	7660	0.17	0.20	0.16	2880	6720
4-25-41	7670	0.07	0.10	0.09	2120	5650
9- 9-41	11,800	0.20	0.26	0.29	2720	4260
6-17-42	7750	0.22	0.12	0.10	1960	5270
7- 2-42	23,100	0.17	0.16	0.20	2570	17,200
9-10-42	18,300	0.33	0.24	0.24	830	17,600
10-22-42	18,600	0.26	0.28	0.27	2690	18,100
11- 3-42	5720	0.51	0.48	0.43	1240	4190
1- 8-43	8190	0.07	0.10	0.08	1130	6560
2-13-43	4430	0.05	0.06	0.04	451	3880
4-16-43	4560	0.03	0.04	0.03	495	3980
5-15-43	8720	0.14	0.18	0.15	2680	4860
5-17-43	43,500	0.72	0.84	0.86	2250	3140
5-27-43	22,200	0.17	0.19	0.22	2720	13,800
6- 9-43	7420	0.05	0.10	0.10	1240	5960
6-21-43	4030	0.03	0.03	0.03	623	3500
7-23-43	8620	0.16	0.20	0.13	364	8590
3-20-44	16,900	0.57	0.57	0.53	2350	14,900
3-21-44	25,500	0.57	0.56	0.53	2220	21,700
3-21-44	26,600	0.66	0.68	0.56	2220	21,700
3-27-44	16,800	0.22	0.25	0.25	1860	16,600
3-28-44	11,400	0.19	0.19	0.23	1120	9610
4- 3-44	5120	0.06	0.05	0.06	556	3730
4- 5-44	5300	0.05	0.03	0.02	1290	3440
4-17-44	20,800	0.34	0.25	0.31	2550	18,800
4-17-44	21,300	0.22	0.23	0.28	2550	18,800
4-29-44	61,800	0.18	0.27	0.27	2690	66,100
5-15-44	11,600	0.09	0.09	0.09	1260	9970
5-16-44	10,900	0.12	0.11	0.11	1160	9260
5-26-44	7400	0.11	0.08	0.11	964	5050
5-27-44	8980	0.07	0.07	0.08	1180	4700
6- 5-44	10,700	0.13	0.13	0.15	1960	8590
6- 5-44	10,400	0.13	0.12	0.14	1960	8590
6-12-44	20,800	0.53	0.53	0.44	1760	12,300
6-13-44	28,100	0.51	0.47	0.47	2020	15,300
6-21-44	8100	0.19	0.19	0.17	1240	5300
6-27-44	11,500	0.22	0.22	0.22	2650	8100
6-30-44	4900	0.05	0.04	0.05	616	3350
7-21-44	4160	0.04	0.04	0.04	846	3080
7-27-44	4470	0.26	0.28	0.29	1830	2670
8- 1-44	4400	0.18	0.20	0.22	1640	2750
8-10-44	5050	0.14	0.15	0.14	283	5300
8-30-44	8540	0.28	0.28	0.28	192	8920
9- 2-44	8990	0.28	0.27	0.25	177	9610
9- 6-44	6670	0.17	0.16	0.14	311	5830
9-30-44	34,800	0.80	0.91	0.74	476	25,000
	Average	0.24	0.26	0.26		

The results of suspended sediment samples collected at Tulsa over a period of more than four years are shown in Tables 1 and 2. To conserve space only samples which were taken with discharges greater than 4000 cfs are shown. In Table 1 the discharge 24 hours previously at Mannford, the stream gaging station about 20 river miles upstream from the mouth of the Cimarron River is less than 3000 cfs, while in Table 2 the discharge is more than 3000 cfs. This rate of flow seemed to give more significant division of results than any other value.

Table 2--Concentration of suspended sediment samples taken at various points in cross-section of Arkansas River, Twenty-First Street Bridge, Tulsa Oklahoma, Mannford discharges greater than 3000 cfs

Date	Discharge at Tulsa	Suspended sediment concentration by weight			Average daily discharge on previous day at upstream stations	
		Left bank sample	Mid-stream sample	Right bank sample	Mannford (Cimarron River)	Ralston (Arkansas River)
	cfs	pct	pct	pct	cfs	cfs
4-17-41	37,300	0.55	0.71	0.80	6280	25,100
5- 8-41	32,400	0.32	0.67	1.16	20,100	13,900
5-24-41	21,300	0.25	0.56	1.00	14,500	4480
6-12-41	68,400	0.36	0.51	0.65	22,700	48,600
11-24-41	14,300	0.19	0.16	0.25	7570	7150
4-27-42	73,300	0.21	0.93	1.14	27,200	35,100
5- 5-42	19,900	0.29	0.36	0.38	4060	15,400
6- 9-42	16,300	0.59	0.61	0.74	5370	3880
6-11-42	24,500	0.40	0.34	0.47	12,400	13,700
6-23-42	98,600	0.32	0.38	0.33	12,700	80,300
6-24-42	137,000	0.35	0.58	0.59	12,600	83,000
6-25-42	120,000	0.24	0.28	0.45	29,600	90,200
10- 7-42	18,300	0.53	0.61	0.68	3340	15,800
5-12-43	25,300	0.29	0.46	0.49	13,100	9960
5-18-43	92,600	0.73	0.60	0.83	23,400	18,800
5-22-43	112,000	0.37	0.51	0.41	34,900	89,500
5-23-43	67,100	0.21	0.28	0.26	14,200	59,200
5-25-43	20,100	0.12	0.15	0.16	4140	15,700
10-24-43	19,500	0.51	0.66	0.64	11,200	935
10-25-43	8150	0.34	0.41	0.36	8700	995
10-27-43	4500	0.26	0.42	0.49	4200	1390
3-17-44	6500	0.22	0.22	0.29	4060	2140
3-24-44	45,600	0.50	0.60	0.80	7570	34,900
3-26-44	30,000	0.40	0.41	0.45	3130	28,900
4-12-44	99,000	0.56	0.64	1.07	44,600	62,200
4-13-44	83,100	0.38	0.40	0.53	26,000	65,700
4-15-44	47,600	0.33	0.39	0.34	4370	47,500
4-24-44	72,300	0.87	1.07	1.30	3100	22,600
4-26-44	171,000	0.22	0.66	0.53	6480	152,000
4-27-44	124,000	0.46	0.40	0.42	4160	128,000
5- 4-44	56,600	0.36	0.45	0.43	10,300	46,700
5- 8-44	33,100	0.28	0.31	0.32	5440	31,900
5- 9-44	26,900	0.30	0.32	0.31	3300	25,700
5-21-44	18,100	0.44	0.50	0.53	4420	7620
5-22-44	9900	0.11	0.12	0.11	3340	7160
6-14-44	31,800	0.58	0.60	0.53	6000	13,600
6-17-44	12,300	0.20	0.23	0.25	5580	7310
7-14-44	12,800	0.31	0.35	0.42	5030	8920
	Average	0.37	0.47	0.55		

In general the samples were collected at the quarter, half, and three-quarter points across the stream section, and were the results either of a complete depth integration of each vertical or of a 0.6-depth observation in the vertical, depending upon what type of sampler was available at the time of sampling. It will be noted that when discharges at Mannford were below 3000 cfs there was no significant difference in the concentration of suspended sediment across the stream at Tulsa, but when discharges at Mannford were above 3000 cfs there was a rather consistent tendency for the concentration to increase from left to right bank, the average increase being almost 50 per cent. The visible evidence that conditions varied across the river took the form of a gradual but noticeable change from brown to red in the color of water flowing under the bridge as it was crossed from left to right bank. The sediment samples collected showed a similar variation in color. It would be interesting at some future date to attempt to show the contrast by means of color photography. The tests at Tulsa show that the Cimarron River has a tendency to retain its identity with reference to suspended sediment concentration even after flowing through 18 miles of channel below its confluence with the Arkansas River.

Table 3--Concentration of suspended sediment samples taken at various points in cross-section of Arkansas River, U. S. Highway 62 Bridge, Muskogee, Oklahoma

Date	Discharge at Muskogee	Suspended sediment concentration by weight			Average daily discharge at upstream stations	
		Left bank sample	Mid-stream sample	Right bank sample	Tulsa[a] (Arkansas River)	Wagoner[a] (Grand River)
	cfs	pct	pct	pct	cfs	cfs
6-18-43	30,000	0.02	0.02	0.02	5120	17,000
6-22-43	14,200	0.01	0.03	0.05	4100	8800
6-29-43	68,300	0.03	0.10	0.18	9200	32,000
7- 7-43	12,400	0.04	0.07	0.06	2850	7800
10-27-43	18,900	0.02	0.28	0.36	8020	5690
2- 9-44	24,200	0.11	0.27	0.27	2180	12,100
3- 1-44	21,700	0.04	0.11	0.15	1760	11,600
3- 8-44	12,200	0.01	0.03	0.04	1660	8460
3-20-44	66,000	0.09	0.24	0.43	17,100	17,200
3-29-44	46,500	0.05	0.06	0.17	11,500	29,800
4- 5-44	15,200	0.03	0.05	0.06	5390	7080
4-13-44	130,000	0.25	0.46	0.53	96,100	12,600
4-19-44	156,000	0.07	0.10	0.16	17,000	67,600
4-26-44	161,000	0.60	0.79	0.83	90,500	13,900
5- 4-44	155,000	0.15	0.11	0.28	49,900	58,100
5-11-44	74,000	0.06	0.10	0.27	24,800	15,400
5-17-44	21,500	0.03	0.10	0.10	10,700	7980
5-24-44	21,700	0.03	0.15	0.93	8680	7160
6- 1-44	27,500	0.07	0.17	0.16	12,700	7020
6- 7-44	17,900	0.03	0.14	0.27	9800	6680
6- 8-44	16,800	0.03	0.14	0.14	8680	6650
6-16-44	44,500	0.19	0.48	0.58	27,100	8630
6-22-44	45,000	0.25	0.26	0.22	8020	33,700
8-31-44	17,200	0.04	0.12	0.15	8020	6610
9- 8-44	14,800	0.02	0.13	0.14	6550	5260
	Average	0.09	0.18	0.26		

[a]Previous day [b]Same day

In Table 3 are shown the results of similar samples collected at Muskogee over a period of somewhat more than a year. Only samples which were taken with discharges greater than 12,000 cfs are shown. Nearly all such samples show increasing sediment concentration from left to right bank. It will be noted that while the average percentage increases almost 200 per cent across the river, the water is generally much less turbid at Muskogee than at Tulsa. This is borne out by the fact that the left bank water at Muskogee often has a clear greenish-blue appearance and there is usually a well defined "boiling" boundary between the red and greenish-blue water. A definite boundary of this kind between red and brown water at Tulsa has not been observed.

The Grand River, which furnishes much of the clear, left-bank water at Muskogee, drains the flint-hill region of southeastern Kansas and the western slopes of the Ozark Mountains in Missouri, Arkansas and Oklahoma. Its limited suspended sediment load is further reduced by the multiple-purpose reservoir formed by the Pensacola Dam about 75 river miles above the mouth of the river.

Samples collected since October 1, 1944, while not thoroughly analyzed, show a continuing substantiation of the results given in the tables.

The observations presented here are not expected to have much practical value in the design of river improvement projects, for in the study of density currents it is vertical rather than horizontal distribution of sediment which is important. However, it is conceivable that the presence of heterogeneous currents of this type could determine the location of intake structures for water supply, navigation, irrigation or other projects which depend to some extent on turbidity of water.

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SNOW SURVEY VERSUS WINTER PRECIPITATION FOR FORECASTING RUNOFF OF THE TUOLUMNE RIVER, CALIFORNIA

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Abstract--This paper is an attempt to analyze the available data to show by comparison the relative accuracy of snow surveys and winter precipitation as applied to forecasting the spring and summer runoff of a typical Sierra Nevada western-slope river.

Fifteen years of snow-survey data were available, and the same years of precipitation were used in the comparison. It was obvious on examination of the graphs that several years, four in the case of snow surveys and three in the case of precipitation, were much out of harmony with the other years. Justification for these discrepancies was found; they were usually caused by abnormal fall or spring precipitation. These years with abnormal precipitation were omitted in determining the position of the line on the graph showing the relationship of snow-water equivalent or of winter precipitation to streamflow. The conclusion in favor of snow surveys seems fully justified.

Introduction--The Tuolumne streamflow data used in this analysis were supplied by Fred Paget for the California Cooperative Snow Surveys. The April-July normal natural flows for Hetch Hetchy and La Grange gaging stations are the averages for the 55-year period, 1890-1944, inclusive, corrections having been made for changes in reservoir storage, evaporation, and diversions. The snow-survey data are taken from the California Cooperative Snow-Surveys' Bulletins covering the 15 years 1930-1944, inclusive. The precipitation data are from United States Weather Bureau publications, and are used only for the same 15 years for which snow-survey data are available.

Table 1--Watershed zone areas

Gaging-station altitude	Hetch Hetchy		La Grange	
ft	mi^2	pct	mi^2	pct
Above 9000	255	55.3	286	31.0
9000 to 7500	129	28.0	254	27.6
7500 to 4000	77	16.7	381	41.4
Total above 4000[a]	461	100	921	100

[a] Elevation 4000 ft considered below April 1 snow line.

Altitude zones--Paget furnished the data in Table 1 concerning watershed areas tributary to the river above the points of gaging.

Snow-survey courses--There are 14 snow courses listed for the Tuolumne Basin, four above 9000 ft altitude, two between 9000 and 7500, and eight below 7500, the lowest, 5700 ft, being at Strawberry Lake.

In determining the relationship between snow surveys and runoff, three of these lower courses were omitted, as in certain years they had little or no snow on April 1, being much out of harmony with other courses probably caused in general by early melting. These three courses are Smith Meadows, altitude 6600; Cottonwood Meadows, 6000; and Strawberry Lake, 5700. It sometimes happens that for the majority of years a certain one or two snow courses in a basin will evidence a close relationship to runoff from that basin. However, I thought it best to use nearly all of the available courses in this analysis.

Abnormal factors--Greatly excessive or deficient spring or "runoff-season" precipitation often has a marked effect on runoff. Abnormal fall precipitation probably has some effect also on the next April-July runoff, though it is not as great in quantity. Heavy winter runoff, usually caused by high temperature or winter rains, generally means less spring runoff, though the April 1 snow surveys in lower altitudes should give a check on this condition. However, high-altitude snow courses in the Central Sierras seldom lose by winter melting and will even absorb considerable rain without runoff if the snow blanket is deep. High or low ground water has a marked effect on runoff because of the small or large demand on the early snow melt if the ground is not frozen under the snow blanket.

For purposes of studying some of these abnormal factors Table 2 is given. The precipitation stations included are as follows: Tamarack located at Blue Lakes, Twin Lakes, Lake Eleanor, Hetch Hetchy, West Point, and Sonora. Further reference will be made to Table 2 in discussions of relationships of results of snow surveys to runoff.

Table 2--Data for abnormal factors

Year	Precipitation in per cent of normal[a]			Winter runoff in per cent of 15-year average[b]	
	October-November	April-June	April	December-March	December-February
	pct	pct	pct	pct	pct
1930	3	95	105	53	42
1931	117	88	70	28	26
1932	115	97	80	110	126
1933	18	93	34	29	22
1934	52	62	13	47	29
1935	158	212	379	76	81
1936	83	98	80	129	144
1937	28	59	79	102	101
1938	93	115	155	220	224
1939	116	65	28	54	43
1940	79	30	39	159	151
1941	64	124	177	137	141
1942	83	209	241	117	142
1943	184	74	81	166	153
1944	66	120	159	55	44

[a] These percentages of normal are based on United States Weather Bureau normals and are averages for the five or six Weather Bureau stations, there being no record for Tamarack for the years 1929-1939. The Weather Bureau had not adopted a normal for West Point, so an estimated normal was determined by comparison with the other stations.

[b] These winter runoff data are for the La Grange gaging station.

The "April" column in Table 2 is given because April precipitation is more effective in producing runoff than May or June precipitation, as much of it falls on snow blanket, while most of the May and nearly all of the June precipitation falls on bare ground, and little of it reaches the streams by surface flow except from heavy showers. Furthermore, a knowledge of abnormal April precipitation will help in making a revised May 1 forecast.

Table 3--Runoff in thousands of acre feet and in per cent of normal (55 years)

Year	April				May				June				July				April-July				Runoff[a]
	Hetch Hetchy		La Grange		Hetch Hetchy		La Grange		Hetch Hetchy		La Grange		Hetch Hetchy		La Grange		Hetch Hetchy		La Grange		
	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	ac ft	pct	pct
1930	96	100	247	81	140	59	277	57	186	74	285	67	29	29	46	30	451	66	855	62	75
1931	77	80	157	52	125	53	207	43	31	12	47	11	7	7	10	7	240	35	421	31	50
1932	77	80	244	80	230	97	519	107	326	130	535	125	107	108	174	114	740	108	1472	107	108
1933	63	66	183	60	123	52	270	56	257	103	405	95	42	42	74	48	485	71	932	68	80
1934	91	95	187	62	90	38	149	31	62	25	96	22	11	11	12	8	254	37	444	32	55
1935	111	115	468	154	234	98	531	109	318	127	512	120	64	65	110	72	727	106	1621	118	100
1936	137	143	395	130	284	119	521	107	244	98	392	92	82	83	123	80	747	109	1431	104	108
1937	75	78	297	98	323	136	633	130	240	96	396	93	59	60	92	60	697	102	1418	103	106
1938	109	113	424	139	300	126	721	148	430	172	713	167	196	198	306	200	1035	151	2164	158	140
1939	126	131	212	70	126	53	218	45	44	17	68	16	10	10	17	11	306	45	515	38	55
1940	102	106	327	108	311	131	572	118	226	90	348	81	35	35	54	35	674	99	1301	95	104
1941	62	64	282	93	301	126	664	137	331	132	536	125	151	152	225	147	845	124	1707	124	119
1942	93	97	344	113	192	81	474	98	364	146	599	140	169	171	254	166	818	119	1671	122	112
1943	140	146	392	129	278	117	498	102	225	90	346	81	101	102	135	88	744	109	1371	100	107
1944	55	57	166	55	215	90	456	94	160	64	268	63	60	61	88	58	490	72	978	71	75
Normals	96	...	304	...	238	...	486	...	250	...	428	...	99	...	153	...	683	...	1371	...	...

[a] Adjusted by considering fall and spring precipitation. These adjusted values used in estimating snow-survey normals. One set of snow-course normals should answer for both Hetch Hetchy and La Grange.

Table 4--Snow surveys, April 1 snow-survey water

Year	Above 9000 ft										9000 to 7500 ft					
	Fletcher Lake, 10,300 ft		Tioga Pass, 9900 ft		Dana Meadows, 9700 ft		Center Mountain, 9400 ft		Average		Tuolumne Meadows, 8600 ft		Lower Relief Valley, 8300 ft		Average	
	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct
1930	25.0	69	22.1	75	19.5	59	28.6	69	23.8	68	14.3	57	30.0	68	22.2	63
1931	12.4	34	9.9[a]	34	13.0	40	18.1	44	13.4	38	7.4	29	18.6	42	13.0	36
1932	39.0	107	35.0	119	39.5	120	47.3	115	40.2	115	35.8	142	56.5	128	46.2	135
1933	25.5	70	17.2	59	22.4	68	29.0	70	23.5	67	20.4	81	30.1	68	25.2	74
1934	17.1	47	16.9	58	18.0	55	23.6	57	18.9	54	3.0	12	19.5	44	19.5	44
1935	30.5	84	24.9	85	29.6	90	37.4	91	30.6	88	21.2	84	43.7	99	32.5	92
1936	40.3	111	34.9	119	35.5	108	45.6	110	39.1	112	30.1	119	43.5	99	36.8	109
1937	47.9	132	...	...	43.0	131	49.0	119	46.6	127	34.5	137	48.4	110	41.4	123
1938	43.9	121	...	...	43.5	132	61.7	150	49.7	134	44.7	177	64.2	146	54.4	161
1939	18.0	50	12.4	42	18.0	55	24.7	60	18.3	52	10.2	41	21.6	49	15.9	45
1940	43.6	120	34.9	119	35.1	107	44.8	109	39.6	114	28.0	111	54.2	123	41.1	117
1941	53.3	147	38.4	131	38.5	117	46.8	114	44.2	127	31.4	125	54.2	123	42.8	124
1942	42.1	116	34.4	117	36.5	111	44.5	108	39.4	113	24.1	96	44.2	100	34.2	98
1943	41.7	115	34.9	119	37.7	115	...	...	38.1	116	...	...	52.1	118	52.1	118
1944	25.9	71	21.6	74	27.1	83	29.7	72	26.1	75	19.2	76	32.5	74	25.9	75
Runoff, average per cent of normal	92.9		88.3		92.9		91.9		...		91.9		92.9		...	
Total snow-survey water equivalents	506.2		337.5		456.9		530.8		...		324.3		613.3		...	
Average snow-survey water equivalents	33.7		26.0		30.5		37.9		...		23.2		40.9		...	
Normals of snow-survey water equivalents	36.3		29.4		32.8		41.2		...		25.2		44.0		...	

[a] Not used in determining average.

The precipitation at the various United States Weather Bureau stations was generally quite harmonious in percentage of normal, though occasionally there was a marked difference between the high-level and low-level stations. More detail will be given concerning these Weather Bureau stations in connection with the analysis of the relationship between April-July runoff and December-March precipitation.

Runoff--Table 3 shows the April-July runoff at both Hetch Hetchy and La Grange gaging stations by months, and totals in thousands of acre feet and in percentage of normals. The adjusted values shown below the actual values are the results of an attempt to estimate what the April-July runoff would have been in percentage of normal if all factors other than snow-water equivalent (in particular the fall and spring precipitation), had been normal. No mathematical method was used in this adjustment, as the writer does not believe it is yet feasible to determine a correct value for the effect of any given departure from normal in spring or fall precipitation.

Snow-survey normals--The first year of snow surveys on these Tuolumne Basin snow courses was 1930. Center Mountain, however, had been surveyed previously by the Nevada Cooperative Snow Surveys in connection with forecasting the runoff of the Walker Basin on the eastern slope of the Sierras. Nine of the total 14 courses were surveyed in 1930, four of them for all 15 years, and the others for most of the years 1930 through 1944, the last year used in this analysis.

In determining the April 1 normal for any snow course, the average water equivalent for all of the available years was related to the average percentage of normal runoff for those same years, using the adjusted percentages of Table 3.

equivalents and per cent of normal by altitude zones

Below 7500 ft																	
Gin Flat, 7100 ft		Upper Kibby Ridge, 6700 ft		Smith Meadows[a], 6600 ft		Beehive Meadows, 6500 ft		Bell Meadows, 6500 ft		Lower Kibby Ridge, 6200 ft		Cottonwood Meadows[a], 6000 ft		Strawberry Lake[a], 5700 ft		Average	
inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct
25.6	66	...	...	...	...	20.0	69	...	...	...	...	...	...	2.7	...	22.8	68
22.9	59	...	...	...	...	...	...	...	...	...	...	...	...	0	...	22.9	59
51.4	132	...	...	...	...	36.0	123	...	...	...	...	...	...	17.1	138	43.7	127
37.2	96	...	...	...	...	28.3	97	...	...	...	...	...	...	16.6	134	32.8	97
12.3	32	...	...	...	...	10.8	37	...	...	...	...	...	...	0	...	11.6	35
43.6	112	...	...	...	...	37.3	128	...	...	...	...	...	...	16.6	134	40.4	120
40.3	103	...	...	...	...	35.0	120	...	...	...	...	...	...	6.7	54	37.6	111
46.7	120	34.5	138	...	...	36.8	126	29.5	136	41.2	129	17.8	140	12.7	102	37.7	130
59.5	153	42.8	171	30.6	266	44.5	152	43.2	199	51.0	160	26.8	211	30.7	248	48.2	167
23.6	61	14.2	57	4.5	39	17.8	61	9.3	43	19.7	62	1.6	...	0	...	16.9	57
80.7	79	19.4	78	2.5	22	21.2	73	15.0	69	26.3	82	0	...	0	...	22.5	76
44.5	114	31.4	125	13.8	120	29.5	101	22.7	105	38.6	121	6.2	49	0	...	33.4	113
42.0	108	25.8	103	13.7	119	30.9	106	23.1	106	33.9	106	9.5	75	7.9	64	31.1	106
27.9	72	16.9	68	5.6	49	22.3	76	16.4	75	23.8	75	0	...	3.0	...	21.5	73
33.2	85	19.7	79	11.0	96	21.8	75	18.4	85	25.9	81	10.4	82	11.4	92	23.8	81
92.9		102.3		101.7		96.0		102.3		102.3		110.4		101.1		...	
541.4		204.7		81.7		392.2		177.6		260.4		70.7		125.4		...	
36.1		25.6		11.7		28.0		22.2		32.6		14.1		12.5		...	
38.9		25.0		11.5		29.2		21.7		31.9		12.7		12.4		...	

Table 4 gives the data for the 14 snow courses--the bottom row containing the normals determined as above described. The percentages of normal entered in the Table were, of course, computed after the bottom row of normals was determined. Table 4 shows the altitudes of the courses, and it will be seen that four of them are in the high-altitude zone, above 9000 ft, two between 9000 and 7500 ft, and the others below 7500. Averages of water equivalent and percentages of normal by altitude zones are also given.

All 15 years were used in determining normals at Fletcher Lake, Dana Meadows, Lower Relief Valley, and Gin Flat; all years except 1937 and 1938 at Tioga Pass; all years except 1943 at Center Mountain; all except 1944 at Tuolumne Meadows; only 1937 through 1944 at Upper Kibby Ridge, Bell Meadows, and Lower Kibby Ridge; only 1938 through 1944 at Smith Meadows; all except 1931 at Beehive Meadows; only 1937, 1938, 1941, 1942, and 1944 at Cottonwood Meadows; and all but 1931, 1934, 1939, 1940, and 1941 at Strawberry Lake.

A comparison of the normals developed in Table 4 with the normals used by the California Cooperative Snow Surveys shows that for Fletcher Lake, Tioga Pass, Dana Meadows, Center Mountain, Tuolumne Meadows, Lower Relief Valley, Gin Flat, and Beehive Meadows my normals are slightly lower, ranging from 95 to 98 per cent of the values given in the California Cooperative Snow Surveys Bulletin for April 10, 1945. For Strawberry Lake, my normal is higher, being 109 per cent of the California normal. California Cooperative Snow Surveys had not established normals for any of the other courses, which were first surveyed in 1937 and 1938.

Snow-survey and runoff relationships--While there is considerable difference in water equivalent by years and in normals, between the different courses of a given altitude zone, the percentages of normal are in better harmony. The Tuolumne Meadows survey for 1934 is so much out of harmony with other courses that it was not used in the average for the middle zone for that year. Five courses are used for the lower altitude zone for recent years, but only two of them were surveyed previous to 1937, so the averages for those earlier years probably do not represent that zone as well as do the averages for the later years.

Table 5 for relationships of snow surveys to runoff at the Hetch Hetchy gage starts with the zone averages of water equivalent and percentage of normal taken from Table 4. These zone averages are then multiplied, respectively, by the corresponding proportions of drainage area given for the zones in Table 1. The sums of these products represent the weighted values of snow-survey water equivalent and percentage of normal for the whole basin. The right-hand columns contain the actual runoff results for April-July in thousands of acre feet and percentage of normal for Hetch

Table 5--Snow-survey-runoff relationships at the Hetch Hetchy gage

Year	Averages						Averages weighted by areas								Actual April-July runoff results	
	Above 9000 ft		9000 to 7500 ft		Below 7500 ft		0.553 × "Above 9000 ft"		0.28 × "9000 to 7500 ft"		0.167 × "Below 7500 ft"		Entire basin			
	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	1000 ac ft	pct
1930	23.8	68	22.2	63	22.8	68	13.2	37.6	6.2	17.6	3.8	11.3	23.2	67	451	66
1931	13.4	38	13.0	36	22.9	59	7.4	21.0	3.6	10.1	3.8	9.8	14.8	41	240	35
1932	40.2	115	46.2	135	43.7	127	22.3	63.6	12.9	37.8	7.3	21.2	42.5	123	740	108
1933	23.5	67	25.2	74	32.8	97	13.0	37.1	7.1	20.7	5.5	16.2	25.6	74	485	71
1934	18.9	54	19.5	44	11.6	35	10.5	29.8	5.5	12.3	1.9	5.9	17.9	48	254	37
1935	30.6	88	32.5	92	40.4	120	16.9	48.7	9.1	25.8	6.8	20.0	32.8	95	727	106
1936	39.1	112	36.8	109	37.6	111	21.6	62.0	10.3	30.6	6.3	18.5	38.2	111	747	109
1937	46.6	127	41.4	123	37.7	130	25.8	70.3	11.6	34.5	6.3	21.7	43.7	127	697	102
1938	49.7	134	54.4	161	48.2	167	27.5	74.2	15.2	45.1	8.0	27.9	50.7	147	1035	151
1939	18.3	52	15.9	45	16.9	57	10.1	28.6	4.5	12.6	2.8	9.5	17.4	51	306	45
1940	39.6	114	41.1	117	22.5	76	21.9	63.1	11.5	32.8	3.8	12.7	37.2	109	674	99
1941	44.2	127	42.8	124	33.4	113	24.4	70.2	12.0	34.7	5.6	18.9	42.0	124	845	124
1942	39.4	113	34.2	98	31.1	106	21.8	62.6	9.6	27.4	5.2	17.7	36.6	108	818	119
1943	38.1	116	52.1	118	21.5	73	21.1	64.2	14.6	33.0	3.6	12.2	39.3	109	744	109
1944	26.1	75	25.9	75	23.8	81	14.4	41.5	7.3	21.0	4.0	13.5	25.7	76	490	72
Average	32.3	93.3	33.5	94.3	29.8	94.7	...	...	...	...	...	...	...	...	...	...
Normal	35.1	...	35.6	...	31.5	...	...	...	...	...	...	...	...	...	...	...

Table 6--Snow-survey-runoff relationships at the La Grange station

Year	Averages						Averages weighted by areas								Actual April-July runoff results	
	Above 9000 ft		9000 to 7500 ft		Below 7500 ft		0.31 × "Above 9000 ft"		0.276 × "9000 to 7500 ft"		0.414 × "Below 7500 ft"		Entire basin			
	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	inch	pct	1000 ac ft	pct
1930	23.8	68	22.2	63	22.8	68	7.4	21.1	6.1	17.4	9.4	28.2	22.9	67	855	62
1931	13.4	38	13.0	36	22.9	59	4.2	11.8	3.6	9.9	9.5	24.4	17.3	46	421	31
1932	40.2	115	46.2	135	43.7	127	12.5	35.7	12.7	37.3	18.1	52.6	43.3	126	1472	107
1933	23.5	67	25.2	74	32.8	97	7.3	20.8	7.0	20.4	13.6	40.1	27.9	81	932	68
1934	18.9	54	19.5	44	11.6	35	5.9	16.8	5.4	12.1	4.8	14.5	16.1	43	444	32
1935	30.6	88	32.5	92	40.4	120	9.5	27.3	9.0	25.4	16.7	49.7	35.2	102	1621	118
1936	39.1	112	36.8	109	37.6	111	12.1	34.8	10.2	30.1	15.6	46.0	37.9	111	1431	104
1937	46.6	127	41.4	123	37.7	130	14.5	39.4	11.4	34.0	15.6	53.8	41.5	127	1418	103
1938	49.7	134	54.4	161	48.2	167	15.4	41.6	15.0	44.4	19.9	69.1	50.3	155	2164	158
1939	18.3	52	15.9	45	16.9	57	5.7	16.1	4.4	12.4	7.0	23.6	17.1	52	515	38
1940	39.6	114	41.1	117	22.5	76	12.3	35.4	11.3	32.3	9.3	31.4	32.9	99	1301	95
1941	44.2	127	42.8	124	33.4	113	13.7	39.4	11.8	34.2	13.8	46.8	39.3	120	1707	124
1942	39.4	113	34.2	98	31.1	106	12.2	35.1	9.4	27.0	12.9	43.9	34.5	106	1671	122
1943	38.1	116	52.1	118	21.5	73	11.8	36.0	14.4	32.6	8.9	30.2	35.1	99	1371	100
1944	26.1	75	25.9	75	23.8	81	8.1	23.3	7.1	20.7	9.9	33.5	25.1	78	978	71

Hetchy taken from Table 3. These results are used in developing the graphs and tables of relationships between snow surveys and runoff for the 15 years available for this analysis.

Table 6 contains the same kind of data for the La Grange gaging station that Table 5 has for the Hetch Hetchy station. The fact that the zone-areas ratios from Table 1 are quite different for the La Grange gage from the Hetch Hetchy causes minor differences, as will be seen by comparing the snow-survey water equivalent and the percentages of normal in Table 6 with the similar data in Table 5. The runoff in acre feet at La Grange gage is seen to be approximately double that at Hetch Hetchy, as should be expected from the fact that the normals are almost exactly in that ratio. The total drainage areas above 4000 are also two to one. The runoff percentages of normal for the two stations generally check each other within less than six per cent, differing more than ten per cent in only one year, 1935, when the difference was 12 per cent.

Table 7--April-July runoff in per cent of normal and departures of runoff from average-relationship line in per cent of normal

Year	Hetch Hetchy, normal = 683,000 acre feet					La Grange, normal = 1,371,000 acre feet				
	Actual runoff	Water equivalent by snow survey		Winter precipitation		Actual runoff	Water equivalent by snow survey		Winter precipitation	
	ac ft	pct	in	pct	in	ac ft	pct	in	pct	in
1930	66	+ 5	+ 5	- 17	- 17	62	+ 4	+ 5	- 13	- 12
1931	35	+ 2	+ 1	0	+ 1	31	- 2	- 6	+ 4	+ 4
1932	108	(- 14)	(- 14)	(+ 31)	(+ 32)	107	(- 19)	(- 24)	(+ 30)	(+ 30)
1933	71	+ 2	+ 2	+ 13	+ 11	68	- 6	- 7	+ 15	+ 15
1934	37	- 4	- 7	- 13	- 12	32	+ 2	0	- 17	- 17
1935	106	(+ 14)	(+ 15)	(+ 46)	(+ 47)	118	(+ 20)	(+ 16)	(+ 59)	(+ 59)
1936	109	0	- 1	- 1	- 1	104	- 5	- 8	- 8	- 7
1937	102	(- 24)	(- 25)	- 1	- 1	103	(- 24)	(- 22)	- 2	- 2
1938	151	+ 3	+ 3	- 3	- 3	158	- 2	0	+ 7	+ 8
1939	45	+ 1	+ 2	- 5	- 5	38	- 2	+ 2	- 5	- 5
1940	99	- 8	- 7	- 11	- 11	95	0	+ 1	- 18	- 18
1941	124	+ 1	+ 3	+ 10	+ 10	124	+ 5	+ 7	+ 13	+ 13
1942	119	(+ 13)	(+ 16)	(+ 24)	(+ 25)	122	(+ 19)	(+ 22)	(+ 33)	(+ 32)
1943	109	+ 2	- 4	+ 17	+ 17	100	+ 5	- 2	+ 8	+ 8
1944	72	+ 1	+ 3	+ 10	+ 10	71	+ 1	+ 6	+ 14	+ 14
Total departure from normal		29	38	101	99	...	34	44	124	123
Average departure from normal		2.6	3.5	8.4	8.3	...	3.1	4.0	10.3	10.3

Graphs--Figures 1A and 1B for Hetch Hetchy and 2A and 2B for La Grange show graphically the relationships which are expressed in figures in Table 5 and Table 6. The straight-line equations shown on these graphs were determined by the least-squares method of locating the correct average line for a series of points plotted on an X-Y diagram. However, in this determination only 11 of the total 15 points were used. It was seen that on all four graphs a good straight-line fit could be made by ignoring the points for the four years farthest from the line, that is, 1932, 1935, 1937, and 1942. The reason for these four years being abnormal can be pretty well explained.

For 1932, while it is seen from Table 2 that fall and spring precipitation was good, the fact that this season was preceded by four low years in succession must have depleted the ground water so that much of the snow melt was absorbed by the ground, thus decreasing the surface runoff that under normal conditions should be expected from the snow-water equivalent measured about April 1. As a matter of fact our eastern-slope records of the Nevada Cooperative Snow Surveys show that 1927 was the only good above-normal year between 1922 and 1932. The year 1924 was an extremely low one, the first year water was pumped out of Tahoe, the lake surface being below the outlet rim.

It is interesting to note from Table 7 (to be discussed later) that the runoff negative departure from the average line for the year 1932 was considerably greater for La Grange than for Hetch Hetchy, the reason very probably being that this basin contained a large proportion of low-altitude deep soil to absorb the snow melt.

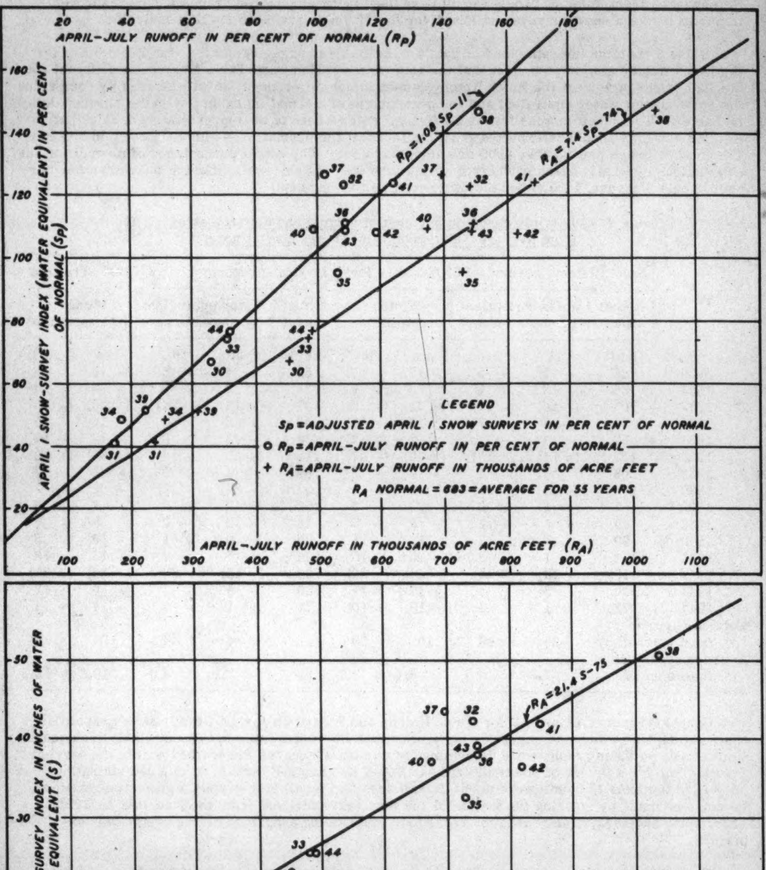

Fig. 1--Snow surveys and runoff at Hetch Hetchy gage for the 15 years 1930-1944, inclusive

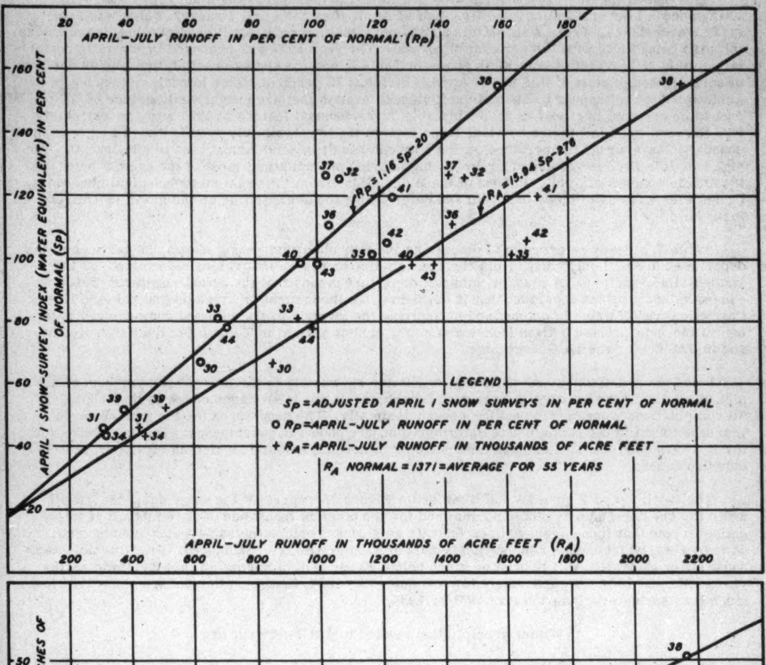

Fig. 2--Snow surveys and runoff at La Grange gage for the 15 years 1930-1944, inclusive

The reason for the high runoff in 1935 in relation to the April 1 snow survey is that very heavy snowfall occurred during the first half of April after the April 1 survey, which was actually made March 22-29. Table 2 shows this as 379 per cent of normal April precipitation, the previous fall also being high, with 158 per cent of normal. The year 1937 was preceded by low fall precipitation, only 28 per cent of normal as shown in Table 2, and the spring precipitation was 59 per cent of normal, though most of this fell in April, which had 79 per cent. This low fall and spring precipitation does not appear to me quite sufficient to explain the large negative departure of 22 per cent to 25 per cent in runoff as shown in Table 7. An unusual feature of 1937 was the extremely cold January, but I fail to see how that helps explain the low April-July runoff, though I believe an unusually low average temperature during May can result in some actual loss in total runoff. The high runoff in 1942 is accounted for by the high spring precipitation, most of the excess being in the efficient month of April. In view of these deviations from the usual meteorological conditions, I think the omission of these four years in determining the average line on the graph is entirely justifiable.

Table 7, already referred to in discussing the four abnormal years, shows, in particular, the departures in April-July runoff from the average-line or theoretical values determined by the straight-line equations. A plus, or positive, departure means that the actual runoff for that year exceeded, and a minus departure that it fell below, the theoretical or average-line value. This theoretical runoff value is determined by applying the formula to the adjusted snow-survey water-equivalent index, shown both in inches and in per cent of normal in Table 5 for the Hetch Hetchy and in Table 6 for the La Grange gage.

Since the runoff and snow-water equivalent are shown only to the nearest full per cent of normal, the sums of the positive and negative departures do not in all cases check as they should if all computations were carried out far enough decimally. The departures for the four abnormal years, not used in the straight-line determination, are shown in parentheses. The departures for the 11 years used are all less than nine per cent of normal, and are as high as eight per cent in only two cases.

The two lines on Figure 1A and likewise on Figure 2A represent the same data, the runoff scale for one being in per cent of normal and for the other in thousands of acre feet. It is interesting to note that these average lines indicate zero runoff before the snow water content gets down to zero, which seems consistent when absorption losses are considered. Probably adjusted snow water equivalent will seldom be much below 40 per cent of normal in this territory as the years 1931 and 1934 were extremely low and quite like 1924, though on the eastern slope 1924 had much less spring precipitation than 1931 or 1934.

Winter precipitation related to April-July runoff

The United States Weather Bureau precipitation stations in or near the Tuolumne Basin used in this analysis, with their elevations, are as follows: Tamarack (at Blue Lakes), 8060 ft; Twin Lakes, 7920 ft; Lake Eleanor, 4665 ft; Hetch Hetchy, 3875 ft; West Point, 2736 ft; and Sonora, 1825 ft. While they are relatively lower than the snow courses, they seem to be the best available and their behavior appears to be quite consistent.

Since most of the precipitation available for an April forecast of April-July runoff occurs in the December-March period, that group of months is used for this analysis. The effect of abnormal previous fall precipitation can be estimated as in the case of snow-survey forecasting.

It was found that for the 15 years under consideration the average December-March precipitation for the six stations was about 110 per cent of normal, based on United States Weather Bureau normals. As the Tuolumne runoff for the same 15 years averages only about 90 per cent of the adopted 55-year normals, it is evident that the relationship of runoff to Weather Bureau percentages of normal on a graph or in a table would be very different from the relationship to snow-survey water equivalent. I decided, therefore, to work for the relationship of runoff to actual adjusted December-March precipitation in inches before using percentages of normal precipitation.

In Table 8 is shown the December-March precipitation in inches at the six stations for the 15 years and the averages by zones, considering Tamarack and Twin Lakes in the high zone, Lake Eleanor and Hetch Hetchy in the middle zone, and West Point and Sonora in the lower zone. Since data are lacking for Tamarack for the years 1929-30 through 1937-38, I estimated the averages as follows: For the remaining six years the average ratio of Twin Lakes precipitation to the average of Tamarack and Twin Lakes was 0.963, so by dividing the Twin Lakes December-March precipitation for each of those nine years by 0.963, or multiplying by its reciprocal, I obtained an estimate of the high-zone average. Of course, the results are not exactly correct for the individual years, but they are probably more nearly correct than if the Twin Lakes values alone had been used, since the Tamarack precipitation exceeds that at Twin Lakes in all but one of the last six years.

Table 8--Winter precipitation, December-March, by altitude zones

Year	High			Medium			Low		
	Tamarack	Twin Lakes	Average	Lake Eleanor	Hetch Hetchy	Average	West Point	Sonora	Average
	in	in	in	in	in	in	in	in	in
1930	...	36.35	(37.8)	24.18	18.69	21.44	24.60	19.96	22.28
1931	...	15.49	(16.1)	12.46	10.24	11.35	11.52	10.55	11.04
1932	...	26.12	(27.1)	38.53	25.43	31.98	26.46	24.56	25.51
1933	...	24.58	(25.5)	23.23	15.70	19.47	17.97	16.32	17.15
1934	...	17.80	(18.5)	22.33	17.61	19.97	20.73	18.01	19.37
1935	...	20.37	(21.1)	28.52	22.20	25.36	21.97	20.33	21.15
1936	...	42.63	(44.2)	37.90	28.24	33.07	40.29	32.46	36.38
1937	...	37.84	(39.3)	41.12	32.19	36.66	33.93	32.68	33.31
1938	...	59.95	(62.3)	51.93	43.00	47.47	44.74	38.82	41.78
1939	23.05	21.05	22.05	19.04	14.30	16.67	13.58	15.26	14.42
1940	39.59	43.25	41.42	44.79	31.65	38.22	39.68	33.00	36.34
1941	52.19	38.30	45.25	43.52	32.60	38.06	33.43	31.28	32.36
1942	39.58	38.50	39.04	34.16	25.51	29.84	31.33	22.18	26.76
1943	36.00	35.61	35.31	36.06	28.14	32.10	33.37	26.94	30.16
1944	26.50	24.64	25.57	24.20	17.20	20.70	21.00	18.32	19.66

I took some liberties in adjusting the precipitation by zones as shown in Table 9, since I applied the same area proportions as used for the higher zones in the snow-survey analysis. I would not pretend to say that the resulting adjusted depth of precipitation applied to the whole area would give a correct quantity of water falling on that area, or that a similar correct quantity determination of water in the whole snow blanket would be obtained by the application of the adjusted snow water equivalent to the area. However, the latter would no doubt be much more nearly correct, since there are more snow courses than precipitation stations, and each snow-course result is the average of numerous measurements taken each year in the same spots, instead of measurements taken at only one spot for each station as in the case of the Weather Bureau precipitation stations. Fortunately, it is not at all necessary to estimate quantitatively the amount of water in the snow blanket or in the total winter precipitation on a watershed.

Table 9 shows the winter precipitation in inches and percentage of normal adjusted by zones for each of the 15 years. In the adjoining colums are the runoff values in thousands of acre feet and percentage of normal, the same as in Table 5 and Table 6 in the snow-survey analysis. Tables 8 and 9 give the data for plotting the graphs and determining the average lines and equations shown in Figures 3 and 4.

As previously explained, the United States Weather Bureau precipitation normals are out of harmony with the 55-year runoff normals. In order to use the percentage of normal relationship, I developed normals for the adjusted values of winter precipitation by assuming that the average adjusted precipitation for the 15 years should be the same percentage of normal as the average runoff for the same 15 years. This resulted in normals of 36.8 inches for the Hetch Hetchy basin and 35.6 inches for the La Grange basin.

Abnormal years--As in the case of the snow-survey analysis, it was found that several years were so far out of harmony with the others that they were omitted in determining the average-relationship lines. In this precipitation-runoff relationship those three years were 1932, 1935, and 1942, the same as three of the four discarded for snow-survey relationship. The same explanations used before will apply for the years 1935 and 1942, as they are on the same side of the determined average line, that is, indicating abnormally high discharge. But the year 1937 has dropped down close to the average line, and 1932 has dropped much below it, apparently indicating abnormally high discharge where abnormally low discharge was indicated in the snow-survey analysis. Since the surveys of the different snow courses were consistently high in water content for both of those years, as seen in Table 4, it is evident that the water was there. I construe the evidence as

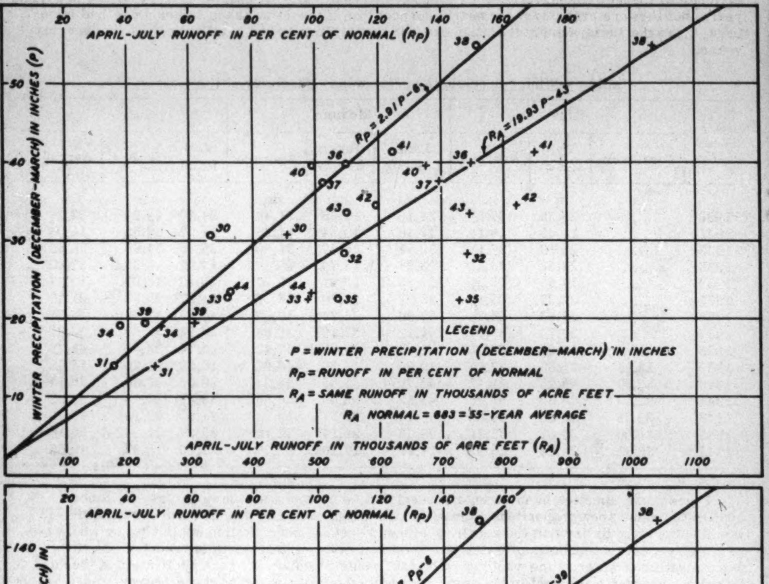

Fig. 3--Winter precipitation and April-July runoff at Hetch Hetchy gage

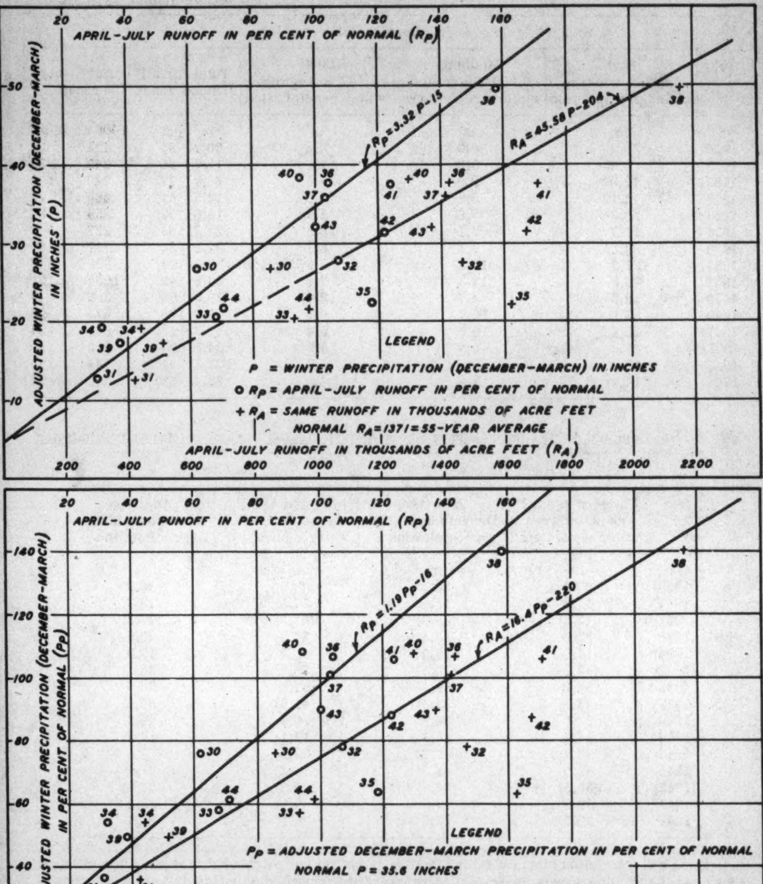

Fig. 4--Winter precipitation and April-July runoff at La Grange gage

Table 9--Winter precipitation

Year	Hetch Hetchy						
	High 0.553 × average winter precipitation	Medium 0.280 × average winter precipitation	Low 0.167 × average winter precipitation	Total for all altitude zones		April-July runoff	
	in	in	in	in	pct	1000 ac ft	pct
1930	20.9	6.0	3.8	30.7	83	451	66
1931	8.9	3.2	1.8	13.9	38	240	35
1932	15.0	9.0	4.3	28.3	77	740	108
1933	14.1	5.5	2.9	22.5	61	485	71
1934	10.2	5.6	3.2	19.0	52	254	37
1935	11.7	7.1	3.5	22.3	61	727	106
1936	24.5	9.3	6.1	39.9	108	747	109
1937	21.7	10.3	5.6	37.6	102	697	102
1938	34.5	13.3	7.0	54.8	149	1035	151
1939	12.2	4.7	2.4	19.3	52	306	45
1940	22.9	10.7	6.1	39.7	108	674	99
1941	25.1	10.7	5.4	41.2	112	845	124
1942	21.6	8.4	4.5	34.5	94	818	119
1943	19.5	9.0	5.0	33.5	91	744	109
1944	14.1	5.8	3.3	23.2	63	490	72

Table 10--Adjusted April 1 snow-survey water equivalents and December-March precipitation

Year	Hetch Hetchy		La Grange	
	Adjusted April 1 snow-survey water equivalent	Adjusted December-March precipitation	Adjusted April 1 snow-survey water equivalent	Adjusted December-March precipitation
	in	in	in	in
1930	23.2	30.7	22.9	26.9
1931	14.8	13.9	17.3	12.7
(1932)	(42.5)	(28.3)	(43.3)	(27.8)
1933	25.6	22.5	27.9	20.5
1934	17.9	19.0	16.1	19.3
(1935)	(32.8)	(22.3)	(35.2)	(22.4)
1936	38.2	39.9	37.9	38.0
(1937)	(43.7)	(37.6)	(41.5)	(36.1)
1938	50.7	54.8	50.3	49.7
1939	17.4	19.3	17.1	17.4
1940	37.2	39.7	32.9	38.5
1941	42.0	41.2	39.3	37.9
(1942)	(36.6)	(34.5)	(34.5)	(31.5)
1943	39.3	33.5	35.1	32.2
1944	25.7	23.2	25.1	21.7

indicating that the United States Weather Bureau gages did not catch what they should in either of those years. In other words, instead of an apparent abnormally high runoff in 1932 and a normal runoff in 1937, I believe the precipitation catch was deficient in both of these winters.

Runoff departures--As evident from inspection of the graphs, Figures 3 and 4, and especially in Table 7, the relationship of winter precipitation to April-July runoff is not so good as the snow-survey-runoff relationship. For the 12 years used in developing the average line for the precipitation analysis, six, and in one case seven, of the years, that is, one-half or more, have runoff departures from ten per cent to 18 per cent of normal, while in the case of the snow-survey relationship, none of the departures exceeded eight per cent of normal. As shown in the tabulation of Table 7, the sum of all the departures of runoff from the average lines divided by the number of years involved (11 for snow surveys and 12 for precipitation), or the average departure per year, is for snow surveys from 2.6 to 4.0 per cent of normal, while for winter precipitation it is from compared with April-July runoff

La Grange						
High 0.310 × average winter precipitation	Medium 0.276 × average winter precipitation	Low 0.414 × average winter precipitation	Total for all altitude zones		April-July runoff	
in	in	in	in	pct	1000 ac ft	pct
11.8	5.9	9.2	26.9	76	855	62
5.0	3.1	4.6	12.7	36	421	31
8.5	8.8	10.5	27.8	78	1472	107
8.0	5.4	7.1	20.5	58	932	68
5.8	5.5	8.0	19.3	54	444	32
6.6	7.0	8.8	22.4	63	1621	118
13.8	9.1	15.1	38.0	107	1431	104
12.2	10.1	13.8	36.1	101	1418	103
19.3	13.1	17.3	49.7	140	2164	158
6.9	4.6	6.0	17.4	49	515	38
13.0	10.5	15.0	38.5	108	1301	95
14.0	10.5	13.4	37.9	106	1707	124
12.2	8.2	11.1	31.5	88	1671	122
10.9	8.8	12.5	32.2	90	1371	100
7.9	5.7	8.1	21.7	61	978	71

8.3 to 10.3 per cent of normal. As for the abnormal years, their departures are also very much greater for the precipitation than for the snow-survey analysis.

It is interesting to note in Table 10 the relative values of the adjusted April 1 snow-survey water equivalent and the adjusted December-March precipitation. It might naturally be assumed that the December-March precipitation should exceed the water equivalent in the April 1 snow blanket, which latter represents residue after some losses. The Table shows that for all of the four abnormal years the value of precipitation is less (in three cases much less) than the value of the snow-survey water equivalent. This is also true in five other years for the Hetch Hetchy and six other years for the La Grange basin. Too much weight should not be attached to this comparison, as the snow-survey courses and United States Weather Bureau stations are at different locations--the snow courses, in general, representing much higher altitudes.

Conclusion--Based on the results of this analysis, the advantage as a basis for forecasting streamflow in the Tuolumne basin appears to be decidedly with snow surveying.

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FORECASTING COLORADO RIVER FLOW

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Abstract--This paper outlines the forecasting work accomplished in the Office of River Control, Region III, U. S. Bureau of Reclamation up to January 1, 1946, where objective methods of forecasting seasonal volume of inflow to Lake Mead are undergoing development. Some of the results and examples of multiple correlation of runoff from the Upper Colorado with snow-survey and precipitation data are presented. There is discussion of forecasts to be made on various dates for various periods, of mass curve adjustment of precipitation records, of the optimum number of stations for multiple correlation, of methods for estimating missing records, and of other factors influencing the precipitation-runoff relation. One of the conclusions of this paper is the need for a long period of record in establishing a reliable system for forecasting.

Introduction

The Upper Colorado River Basin (see Fig. 1) from which comes the major portion of the water entering Lake Mead, covers part of the states of Colorado, Wyoming, Utah, New Mexico, and Arizona. The total drainage area above Boulder Dam, the major storage structure on the Colorado, is reported by the United States Geological Survey as 167,800 square miles. The Colorado, the third longest river in the United States, has its source in the high snow-capped mountains in the northwestern part of the State of Colorado. It is also fed by major tributaries rising in other parts of Colorado; by the Green, rising in Wyoming and flowing to its junction with the Colorado in the southern part of Utah; by the San Juan, which rises in southern Colorado, flows through northern New Mexico and joins the Colorado in southern Utah; and, from the lower basin, by the Little Colorado, which flows northwesterly from its source in east central Arizona to its junction in north central Arizona. In the northern portion of the Basin are hundreds of peaks more than 13,000 feet in elevation. It is the accumulated winter snow at high altitudes, melting in the spring, that supplies 60 to 70 per cent of the toal annual flow in the Colorado. From measurements of the snow cover and of precipitation over the drainage area, forecasts of the springtime flow in the river are made.

The purpose of the forecasts is to make possible the efficient operation of Lake Mead, with proper regard for the functions intended. The Boulder Canyon Project Act provides that the purposes for which Lake Mead and Boulder Dam were constructed have the following order of preference: (1) River regulation, improvement of navigation, and flood control; (2) irrigation and domestic use and satisfaction of perfected rights; and (3) power. The most important source of revenue for repayment of the cost of the dam is sale of power. Therefore, it is highly desirable that maximum possible power production be achieved, at the same time not interfering with the functions of higher priority. In order to accomplish this, it is necessary to have as much foreknowledge as possible of the quantity of inflow to the reservoir.

About 1936 the Denver office of the United States Bureau of Reclamation began the work of forecasting inflow to Lake Mead. After the Regional reorganization of the Bureau in 1943 and the establishment of the Office of River Control in Region III in 1944, responsibility for making forecasts was transferred to that office at Boulder City in 1945.

Snow surveys in the five states of the Upper Basin have been made for several years. The Bureau of Reclamation has contributed financially to the surveys but has made none itself. Data from 78 snow courses on the watershed were received in April, 1945.

Precipitation stations on the watershed, maintained by the United States Weather Bureau, are many in number. For use in forecasting the river flow, those with long records have been selected. Of these, a further selection of 13 stations has been made on the basis of the degree of correlation between precipitation and runoff. Currently, the period of record used is 1913-1945.

For forecasting flow during periods other than springtime, the principle of pattern sequence has been used. That is, forecast for certain periods are made on the basis of the quantity of flow during the preceding three or four months. The basis for all forecast formulas developed in the Office of River Control has been statistical correlation. Such a procedure avoids the chance of personal bias, so often more or less unconsciously present in visual examination, and provides a means of determining probable limits of accuracy of a forecast.

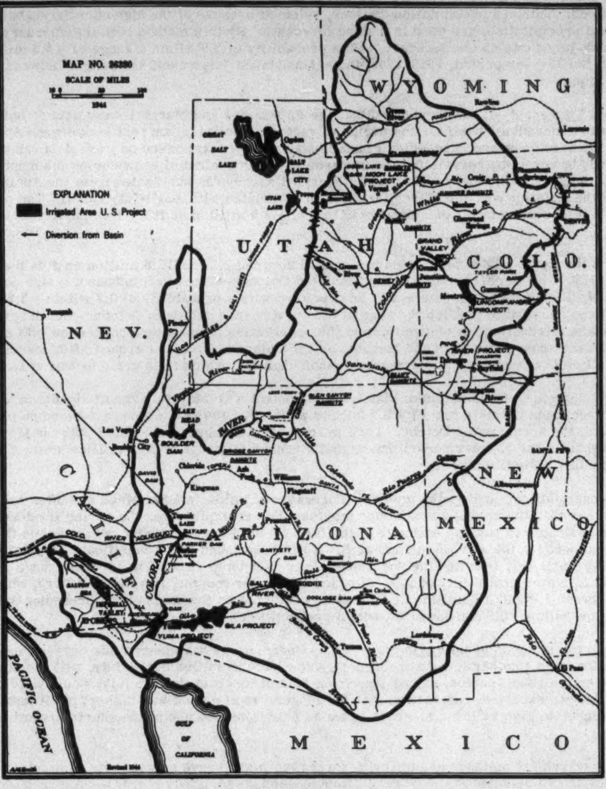
MAP NO. 26380
SCALE OF MILES
10 0 50 100
1944
EXPLANATION
Irrigated Area U. S. Project
Diversion from Basin
WYOMING
UTAH
COLO.
NEV.
ARIZONA
NEW MEXICO
CALIF.
MEXICO
PACIFIC OCEAN
GULF OF CALIFORNIA
GREAT SALT LAKE
SALT LAKE CITY
Ogden
Las Vegas
LAKE MEAD
BOULDER DAM
PARKER DAM
IMPERIAL DAM
COLORADO
RIVER
Kingman
Flagstaff
Williams
Prescott
Tucson
El Paso
Santa Fe
Albuquerque
Gallup
GRAND VALLEY
GILA PROJECT
YUMA PROJECT
SALTON SEA
IMPERIAL VALLEY
SALT RIVER
Revised 1944

Fig. 1--Colorado River Basin

Results of studies

Forecast of the spring and summer inflow into Lake Mead are made on the following four dates: February 1, March 1, April 1, and May 1. The forecasts based on precipitation records are considered reliable, while those based on the 1936-1945 snow data record should be used with caution because the ten-year period is too short to furnish a reliable indication of runoff to be expected under all the varying conditions that may occur. Relationships between snow data and runoff for the available period of record are included below, however, along with those between precipitation and runoff for the longer period, 1913-1945. Conclusions drawn from the snow data relationships are considered as tentative only, because additional years of measurement could cause considerable change in the relationships.

February 1 and March 1 forecasts--Water content of snow as measured on February 1 and March 1 for the ten-year period, 1936-1945, has no significant correlation with succeeding spring runoff. Accumulated precipitation to February 1 and March 1, that is, for the periods, October through January and October through February, has been found to be a fair index of the succeeding spring flood. Thirteen precipitation stations, selected because of the high correlation between runoff and precipitation, are used in making forecasts. By this method both the February-July and March-July flows can be forecast, with a probability of 0.9 within a range of ± 3.3 million ac ft. In the 33-year period, 1913-1945, the actual March-July runoff has ranged between 2.6 and 16.3 million ac ft.

April 1 forecast--It has been noted that the February 1 and March 1 snow data do not correlate with succeeding runoff for the period of record. Similarly, correlation between April 1 water content of snow and succeeding runoff is poor. A forecast based on snow data can be made on April 1, however, by correlating the increase in water content of snow during the month of March with subsequent runoff. That is, the March 1 average is subtracted from the April 1 average, and the difference or the March increase is correlated with April-July runoff. The correlation results in a forecast range, nine chances in ten, of ± 2.9 million ac ft for this particular ten-year period.

When the April-July runoff, which has ranged between 2.2 and 15.6 million ac ft in the 33-year period, 1913-1945, is correlated with accumulated October-March precipitation, a high correlation is attained. Runoff by this formula may be predicted with a probability of 0.9 within ± 2.8 million ac ft. The agreement in prediction range of the snow course data with October-March precipitation data is interesting. It brings to mind the observation of operators concerned with snow-water runoff that the snow which falls and remains on the Colorado River watershed after March 1 is more positive in contribution to springtime runoff than that which falls prior to March 1.

May 1 forecast--Correlation of May 1 water content with May-July runoff results in a prediction range, nine times in ten, of ± 2.7 million ac ft. For the May 1 forecast based on precipitation data, the accumulated October-April precipitation has been correlated with the May-July runoff, which, in the 33-year period, has actually ranged from 1.8 to 13.8 million ac ft. The forecast range is ± 2.3 million ac ft.

Forecasts for fall and winter months--Forecasts of inflow to Lake Mead are often needed for periods other than the spring and summer months. For example, after the spring flood has passed, it may be desirable to have an estimate of the flow during August-October, which has in the past ranged between 0.5 and 4.6 million ac ft. It has been found that a significant correlation exists between the April-July flow and the succeeding August-October flow. The forecast range is ± 1.4 million ac ft, with a probability of 0.9. Flow for the winter months, November-March, which has ranged between 1.4 and 3.6 million ac ft, may be predicted on the basis of the preceding August-October flow within ± 0.8 million ac ft, with a probability of 0.9.

Search for methods of improving forecasts--Correlations have been made between accumulated precipitation from October to date of forecast, and runoff from October to July, with the hope that use of the entire runoff period, rather than from date of forecast through July, would yield better results. As was expected, correlation with the longer runoff period was higher; but it was not sufficiently higher to give as low a forecast range as is obtained by use of the shorter runoff period, May-July.

In the search for methods of improving forecasts, mass curve adjustments of precipitation records for the 13 selected stations were computed, and the adjusted records were correlated with runoff. The result was a slightly poorer correlation than obtained by use of unadjusted records.

The possibility of predicting total inflow to Lake Mead by combining predictions for contributing sub-basins was investigated. Correlation in most of the sub-basins were so low that they were of no practical value.

It will be noted that the forecast procedures summarized above, with one exception, are based on simple correlations between only two variables. Because of the wide ranges in the forecasts it might be supposed that introduction of other variables would result in better correlations. With this thought in mind, numerous combinations of other variables with precipitation, such as temperature, evaporation, wind movement, and solar radiation, have been correlated with runoff. In addition, multiple correlations with runoff, using precipitation occuring in each month as separate variables, have been made. Precipitation amounts occuring in various areas have been used as separate variables, as well as amounts occurring at various elevations. It has not been possible thus far to reduce the forecast ranges by these processes.

For the purpose of determining the adequacy of precipitation records as index of runoff, the precipitation occurring in past years, after May 1, has been included in the correlation with May-July runoff. No improvement in correlation was attained. That is, even if the amount of precipitation which would occur during May-July were known beforehand, the forecast range for the May-July runoff would be ± 2.1 million ac ft, only slightly smaller than when using the accumulated October-April precipitation. It appears, then, that the trend has been fairly well established by May 1, as far as precipitation is concerned, and that later precipitation is only a minor cause of error in the forecasts. Other variables as yet undiscovered would appear to be mainly responsible for the difference between predicted and actual runoff.

From the summary given above, from the discussion to follow, and from the many other papers which have been written on the subject, it will be seen that much progress has been made in developing formulas for forecasting Colorado River flow, but that the problem is still far from a final solution. In the Office of River Control at Boulder City, Colorado, there are seven or eight volumes of about 150 pages each, containing computations and results of investigations made during the past year. Examination of these investigations brings to mind many new lines of attack to be tried. Suggestions from others interested in the subject have been, and will be, investigated.

Table 1--Sample computation, May 1 forecast of May-July runoff based on snow data

Year	May-July runoff at Grand Canyon			Avg. water content of 30 snow courses			Correlation Σxy	
	+ y	Y	- y	+x	X	- x	+xy	- xy
	mil ac ft	mil ac ft	mil ac ft	in	in	in		
1936	...	7.3	0.2	...	9.3	1.4	0.28	
1937	...	7.2	0.3	...	9.2	1.5	0.45	
1938	2.2	9.7	...	1.0	11.7	...	2.20	
1939	...	4.5	3.0	...	7.9	2.8	8.40	
1940	...	3.9	3.6	...	7.0	3.7	13.32	
1941	3.3	10.8	...	4.6	15.3	...	15.18	
1942	1.2	8.7	...	0.6	11.3	...	0.72	
1943	...	6.3	1.2	...	5.5	5.2	6.24	
1944	1.7	9.2	...	4.1	14.8	...	6.97	
1945	...	7.3	0.2	3.9	14.6	...		
Totals	8.4	74.9	8.5	14.2	106.6	14.6	+53.76	- 0.78

$n = 10$
$\bar{Y} = 7.5$ mil ac ft

$\Sigma y^2 = 43.63$
$\sigma y = \sqrt{43.63/10}$
$\sigma y = 2.089$ mil ac ft

Error of estimate
$\sigma Est = \sigma y[n(1 - r^2)/(n - m)]^{1/2}$
$0.9^P = t\sigma_{Est}$
$t = 1.86$ (Fishor's t-table)
$0.9^P = \pm 2.75$ mil ac ft

$n = 10$
$\bar{X} = 10.7$ mil ac ft

$\Sigma x^2 = 107.32$
$\sigma x = \sqrt{107.32/10}$
$\sigma x = 3.276$ mil ac ft

Regression equation
$y = bx + a$
$b = r(\sigma y/\sigma x)$
$= 0.774(2.089/3.276)$
$b = 0.494$ mil ac ft/in
$Y = bx + a, \; a = 2.3$
$Y = 0.49X + 2.3$

$53.76 - 0.78 = 52.98 = \Sigma xy$
$r_{yx} = (\Sigma xy/n\sigma_y\sigma_x)$
$= 52.98/10 \times 2.089 \times 3.276$
$= 0.7742$
$\sigma r = (1 - r^2)/\sqrt{n - m}$
$= 0.142$ = stand. error
$r_{yx} = 0.7742 \pm 0.142$
n = number of years = 10
m = number of variables = 2
n - m = degrees of freedom
Note: σ_r strictly applicable to n = 100 or more

General discussion

The following discussion describes the principal investigations undertaken. Statistical correlation provides the basis for all forecast formulas developed. For an illustration of the statistical functions involved, Table 1 and Figure 2 have been prepared. The ten-year record is used for the example because the shorter record involves fewer figures, and hence is easier to follow the various operations. It is shown elsewhere that ten years is too short a record for reliable forecasting.

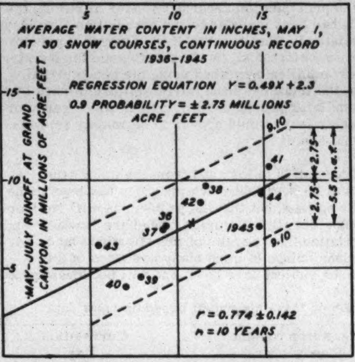

Fig. 2--Relation of runoff at Grand Canyon to water content at 30 snow courses on the Colorado River Watershed

1945 forecast--When development of methods of forecasting flow was begun in the Office of River Control in February, 1945, an immediate and pressing problem was to prepare forecasts of Lake Mead inflow for the coming spring. Data available to the office consisted of snow survey records for the period 1936-1944, and a compilation of precipitation and runoff data made in the Bureau's Denver Office several years ago for the period 1898-1935. With these data, and in the short time available, forecast formulas were derived. For a brief outline of the development of these formulas reference is made to a paper by the authors published in the minutes of the April, 1945 meeting of the Colorado River Water Forecast Committee.

Results of the 1945 forecasts are as shown in Table 2. It will be noted that forecasts based on accumulated precipitation gave the better results.

The compilation of precipitation records used for the above forecasts included nearly all stations on the watershed having sufficiently long records for determination of normals. Records for only a few of the stations were continuous over the entire period, 1898-1935. Precipitation amounts were given in percentages of normal. For use in making the 1945 forecasts, the Office of River Control selected 23 precipitation stations well distributed over the watershed, rather than attempting to obtain current records for all existing stations used in compilation of the 1898-1935 record. Such selection is justified in the same way as is the method used in compiling the long record, the theory being that the average percentage normal of several stations in an area should approximate the average percentage normal of all stations in the area. Current records of the 23 stations were converted to percentage of normal, and forecasts were made on the basis of a correlation using the 1898-1935 record. Investigation of forecast methods carried on since the 1945 runoff season has led to abandonment of the 1898-1935 record as a basis for forecasting, because better correlation and a narrower forecast range have been obtained by use of other precipitation records.

Table 2--Inflow to Lake Mead; forecast range (0.9 probability and actual)

Basis	Feb.-July	March-July	April-July	May-July
	mil ac ft	mil ac ft	mil ac ft	mil ac ft
1936-1944 Snow survey		5.0-12.0[a]	8.3-13.3	9.1-11.1
1898-1935 Precipitation		6.0-14.0	6.0-12.6	6.2-12.0
Actual	9.0	8.6	8.1	7.3

[a] No statistical basis; range determined by envelope lines

The lower limit of the snow data forecast given in Table 2 for May-July, 1945 exceeded the actual by nearly two million ac ft. Some explanation may be in order as to the manner of making the forecast and the reason for its failure. In the nine-year period from 1936-1944 there were two years, 1941 and 1944 in which an increase in snow water content occurred between April 1 and May 1, a decrease occurring in all other years. Further, 1941 and 1944 were years of higher than average runoff for the May-July period. It was partly on the basis of this fact that the 1945 May 1 forecast was made. That is, the change in water content during the month of April was used as a third variable. In 1945 an increase in water content again occurred during April, but this time the increase was not followed by a larger than average yield. Thus, a phenomenon which had occurred twice in the previous nine years was not repeated, even though the same conditions prevailed. Had the record covered many years rather than only nine, it would have revealed whether the basis of the forecast was valid. This experience illustrates the hazard of basing forecasts on so short a record.

Ten-year record inadequate for forecasting--Even though the ten-year record is inadequate for reliable forecasting from snow course data, it is of interest to examine the correlations that now exist between snow-course data and runoff for the 1936-1945 decade, as shown in Table 3.

Table 3--Correlation of snow survey data with runoff

Forecast date	r	Remarks
February 1	0.33 ± 0.36	No significance
March 1	0.13 ± 0.29	No significance
April 1	0.46 ± 0.28	Poor correlation
March increase	0.80 ± 0.13	Highly significant
May 1	0.77 ± 0.17	Highly significant

The question arises as to whether there is any method available that will indicate what may happen to the forecasts, especially the first three, with addition of a large number of years. Since the precipitation data are evidently closely related to snow-course data, the 33-year precipitation record broken down into short records should reveal what is likely to happen to snow-course correlations covering short periods.

The February 1 forecast from precipitation was chosen for trial because the ten-year correlation of snow-course data listed above is poor, but the precipitation correlation with runoff for February 1, based on 33 years, is good. The method is simply to find the decade having the lowest and the highest correlation by means of running averages. These are not samples in the statistical sense because each period contains all but one of the years contained in the previous group. Periods correlated were of ten-year length, with the third and fourth years omitted to agree with the available February 1 snow record, which includes the years 1936-1937 and 1940-1945. Results are presented in Table 4.

Table 4--Short period precipitation-runoff correlations for February 1 forecast

Period	Correlation		Forecast range (0.9 prob)	Period	Correlation		Forecast range (0.9 prob)
	r	Standard error			r	Standard error	
			mil ac ft				mil ac ft
1913-22	0.781	0.159	4.1	1925-34	0.846	0.116	4.3
1914-23	0.736	0.187	3.9	1926-35	0.950	0.040	2.4
1915-24	0.668	0.226	4.2	1927-36	0.893	0.083	3.5
1916-25	0.593	0.265	5.3	1928-37	0.883	0.089	3.4
1917-26	0.615	0.254	5.1	1929-28	0.871	0.099	3.4
1918-27	0.337	0.362	4.2	1930-39	0.739	0.185	4.4
1919-28	0.619	0.252	3.9	1931-40	0.751	0.178	4.3
1920-29	0.555	0.283	5.5	1932-41	0.772	0.163	4.0
1921-30	0.502	0.306	5.1	1933-42	0.884	0.089	3.7
1922-31	0.851	0.113	3.7	1934-43	0.883	0.090	3.7
1923-32	0.900	0.079	2.8	1935-44	0.624	0.249	4.5
1924-33	0.826	0.128	3.6	1936-45	0.678	0.220	3.6

It will be noted that for the ten-year period ending in 1927 the correlation is 0.337 ± 0.362, almost identical with that for February 1 snow data of 1936-1945. Yet the correlation between precipitation and runoff for the long period, 1913-1945, is highly significant 0.82 ± 0.06, giving a prediction range of ± 3.4 million ac ft. If the 1926-1935 record of precipitation were used for the forecast, the prediction range would be ± 2.4 million ac ft. Going back another five years to the 1920-1929 record, the range would be ± 5.5 million ac ft.

When the prediction range for short periods, using precipitation data, can vary so greatly, it is most likely that the same thing will be true for snow data when a long record becomes available. It is improbable, therefore, that any one period of eight or ten years would ever be a reliable source of data for forecasting purposes.

1913-1945 selected as period for forecasts based on precipitation--Forecasts of runoff acually apply to the Grand Canyon gaging station some 190 miles upstream from Lake Mead where stream measurements have been made by the United States Geological Survey since 1923. This provides a continuous measured record of 23 years. Inflow between this station and the Lake is but a small percentage of the total and may be neglected.

It was desired to have a longer reliable record if possible, however, and methods of extending the record were sought. It was found that monthly records of flow at the Grand Canyon station correlated highly with records at the Topock gaging station, about 115 miles downstream from Boulder Dam, where stream measurements have been made since 1917. It was found also that measurements at Yuma, about 200 miles further downstream, when corrected by subtracting the flow in the Gila and Williams Rivers, correlated with the Grand Canyon records. Reproducing records by this method was limited by the fact that records for the Williams River are not available prior to 1913. The period that could be reproduced, therefore, was limited to 1913-1922. Modified Yuma records were used for the period 1913-1916, and the Topock records were used for the period 1917-1922, making a useful record of 33 years in length, that is, 1913-1945.

Selection of stations for use in forecasts based on precipitation--There are about 120 United States Weather Bureau stations where precipitation is measured on the Colorado River Watershed above the Grand Canyon gaging station. Out of that number records for 29 stations meeting the criterion that the record be complete from 1913 to date had been assembled at the time this study was begun. The 29 stations are shown on Figure 3.

It was decided to test each of the station records to determine if elimination of some would improve the correlation with runoff. The method of test employed was simply to correlate individual station records of October-April precipitation with Lake Mead inflow for May-July. Results of these correlations are shown in columns 4 and 5 of Table 5, with the stations listed in descending order of correlation with runoff. The next step was to combine stations records, adding one at a time and correlate the average with runoff. These results are shown in columns 7 and 8 of Table 5. The data of Table 5 are also shown graphically on Figure 4.

Table 5--Individual and group correlations of precipitation with runoff on the Upper Basin of the Colorado River Watershed

No.[a]	Station	State	Individual correlation		Number of stations in group	Correlation of group average		Forecast range (0.9 prob)
			r	$\pm\sigma r$		r	$\pm\sigma r$	mil ac ft
1	Paonia	Colo.	0.741	0.08	1	0.741	0.08	3.5
2	Durango	Colo.	0.671	0.10	2	0.751	0.08	3.4
3	Steamboat Springs	Colo.	0.655	0.10	3	0.848	0.05	2.7
4	Lay	Colo.	0.651	0.11	4	0.866	0.04	2.6
5	Crested Butte	Colo.	0.635	0.11	5	0.866	0.04	2.6
6	Duchesne	Utah	0.633	0.11	6	0.874	0.04	2.5
7	Collbran	Colo.	0.564	0.13	7	0.884	0.04	2.4
8	Delta	Colo.	0.525	0.13	8	0.883	0.04	2.4
9	Fraser	Colo.	0.502	0.14	9	0.903	0.03	2.2
10	Ft. Duchesne	Utah	0.497	0.14	10	0.907	0.03	2.2
11	Montrose	Colo.	0.498	0.14	11	0.906	0.03	2.2
12	Blanding	Utah	0.491	0.14	12	0.896	0.04	2.3
13	Green River	Utah	0.481	0.14	13	0.896	0.04	2.3
14	Escalante	Utah	0.466	0.14	14	0.889	0.04	2.4
15	Castle Dale	Utah	0.458	0.14	15	0.886	0.04	2.4
16	Meeker	Colo.	0.454	0.15	16	0.881	0.04	2.4
17	Watson	Utah	0.422	0.15	17	0.868	0.04	2.6
18	Emery	Utah	0.407	0.15	18	0.861	0.05	2.6
19	Grand Junction	Colo.	0.414	0.15	19	0.858	0.05	2.6
20	Moab	Utah	0.414	0.15	20	0.843	0.05	2.8
21	Sapinero	Colo.	0.410	0.15	21	...	...	..
22	Vernal	Utah	0.389	0.15	22	...	...	..
23	Price	Utah	0.354	0.16	23	0.822	0.06	2.9
24	Hanksville	Utah	0.294	0.17	24	...	...	..
25	Gunnison	Colo.	0.285	0.17	25	...	...	..
26	Green River	Wyo.	0.225	0.17	26	0.799	0.07	3.1
27	Dillon	Colo.	0.164	0.18	27	...	...	..
28	Glenwood Springs	Colo.	0.107	0.18	28	...	...	..
29	Pinedale	Wyo.	0.057	0.18	29	0.788	0.07	3.2

[a] Stations are arranged in order of the correlation of their average October-April precipitation with May-July runoff at Grand Canyon.

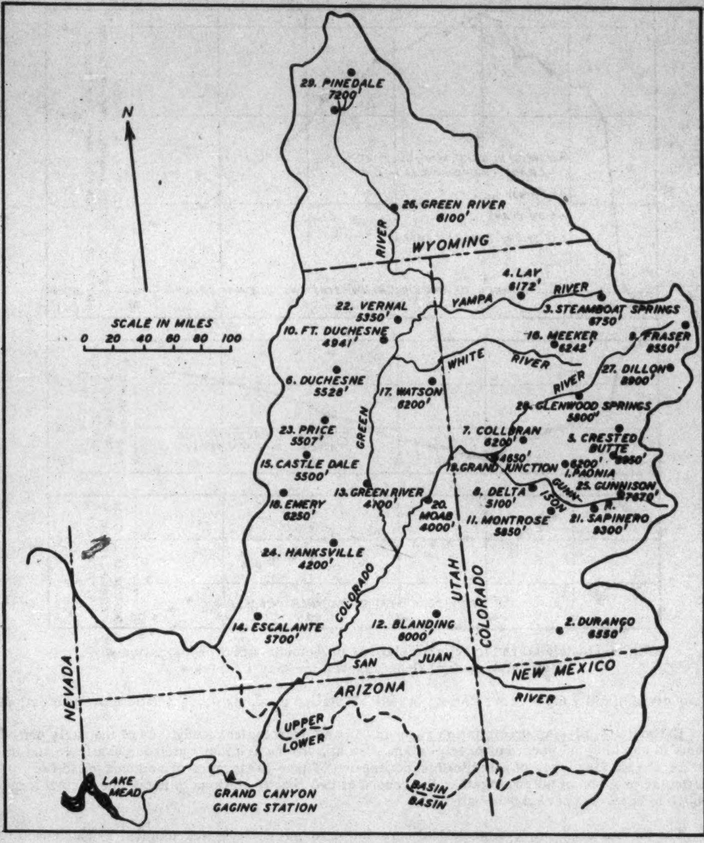
29. PINEDALE
7200'
N
26. GREEN RIVER
6100'
RIVER
WYOMING
4. LAY
6172'
YAMPA
RIVER
3. STEAMBOAT SPRINGS
6750'
22. VERNAL
5350'
10. FT. DUCHESNE
4941'
SCALE IN MILES
0 20 40 60 80 100
16. MEEKER
6242'
9. FRASER
8550'
WHITE
RIVER
27. DILLON
8900'
6. DUCHESNE
5528'
17. WATSON
6200'
RIVER
28. GLENWOOD SPRINGS
5800'
GREEN
23. PRICE
5507'
7. COLLBRAN
6200'
5. CRESTED BUTTE
8850'
15. CASTLE DALE
5500'
4650'
19. GRAND JUNCTION
6200'
1. PAONIA
GUNN-
ISON
25. GUNNISON
7670'
13. GREEN RIVER
4100'
20.
MOAB
4000'
8. DELTA
5100'
R.
18. EMERY
6250'
11. MONTROSE
5850'
21. SAPINERO
9300'
24. HANKSVILLE
4200'
UTAH
COLORADO
COLORADO
14. ESCALANTE
5700'
12. BLANDING
6000'
2. DURANGO
6550'
NEVADA
SAN
JUAN
NEW MEXICO
ARIZONA
RIVER
UPPER
LOWER
BASIN
BASIN
LAKE
MEAD
GRAND CANYON
GAGING STATION

Fig. 3--Precipitation stations in the Colorado River Basin

The first station on the list is Paonia, Colorado with the highest individual correlation r = 0.74. The next correlation uses the average October-April precipitation for two stations, Paonia and Durango, Colorado. The r has begun to rise and is 0.75. The third correlation uses the average precipitation for three stations, Paonia, Durango, and Steamboat Springs, Colorado. The r is 0.85. While the individual station correlation is going down, the correlation of the average of the group is rising until ten stations are included, giving r = 0.907. After that the general trend is downward for the averages as well as for the individual stations. While the highest correlation comes from the first ten stations, groups containing nine to thirteen stations have practically the same correlation. This is about ten per cent of the total number of Weather Bureau stations on the watershed.

The 13-station group has been selected for forecasting purposes rather than the ten-station group because the group average becomes more stable as stations are added. The ten-station

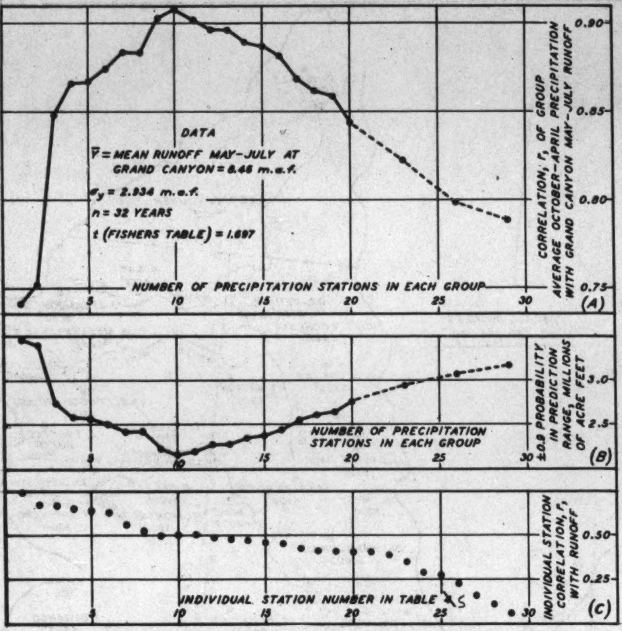

Fig. 4--Individual and group correlations of October-April precipitation with May-July runoff at Grand Canyon for May 1 forecast

group gives slightly higher correlation, but the 13-station grouping gives a little more protection.

Estimate of missing precipitation records--In any hydrological study, one of the early problems is patching the record of precipitation stations. There are many methods available and in use for the various types of substitutions necessary. These paragraphs are addressed to the particular problem of adding together the record of two nearby stations to make one record long enough to cover the period being studied.

The method used employs statistical correlation to define the meteorological neighborhood. Application of the method depends on finding a third station with a record covering a part of the record of each of the two stations under investigation. The next requirement is that records of the third station correlate significantly with records of the two stations to be joined. Then these correlations are an index of the meteorological neighborliness of the third station with the two stations about to be joined.

The record of Craig and Lay, Colorado, is an example. Lay has a long and valuable precipitation record beginning in 1890, but it stops with 1935. Craig's record begins in 1937 and continues to date. Craig is 23 feet higher and 18 miles to the east of Lay. East of Craig, 16 miles and 142 feet higher, is a station at Hayden, Colorado that has a spotty record. Out of it was found 15 years, not consecutive, with an October-April precipitation record that correlated with a corresponding record at Lay, giving an r of 0.846 ± 0.079. There were eight years of the Hayden record that were correlated with the corresponding Craig record, r = 0.756 ± 0.175. These correlations are shown graphically on Figure 5. Using the initial letter for each station, the regression equation for the Lay-Hayden relation is L = 0.72H + 2.6. The regression equation for the Craig-Hayden relation is C = 0.68H + 1.9.

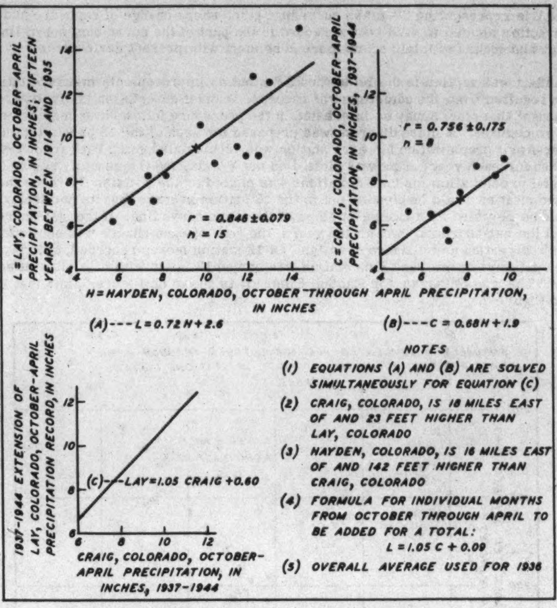

Fig. 5--Extension of Lay, Colorado, October through April precipitation record 1890-1935 by adding Craig, Colorado, October through April precipitation 1937-1944 record adjusted by Equation C

These equations can be solved simultaneously to eliminate H. The resulting equation is: L = 1.05C + 0.60 for the seven-month period October-April. The Craig record thus has become an extension of the Lay record, bringing it up to date.

The method of restoring records by correlation with third record was used on two other combinations: Meeker and Near Meeker, Colorado, and Watson and Bonanza, Utah. Near Meeker is 13 miles northwest and 258 feet higher than Meeker, the old station. The average of Glenwood Springs and Hayden was the best arrangement for a third precipitation record that could be found. Meeker correlated with an r = 0.477 ± 0.23 (n = 13 yrs) and Near Meeker correlated with an r = 0.790 ± 0.14 (n = 9 yrs). The equation for estimate is M = 0.784 N-M + 1.93. This was used for restoring the missing Meeker record for the period 1932-1940. After that the Meeker station began reporting again.

Bonanza is 12 miles north and 750 feet lower than Watson, Utah, the old stations. Vernal, Utah is the missing link. It is 40 miles north northwest and 100 feet lower in elevation than Bonanza. Vernal and Watson correlated with and r = 0.791 ± 0.100 (n = 16 yrs). Vernal and Bonanza correlated with an r = 0.869 ± 0.122 (n = 6 yrs). The estimating equation is V = 0.93B + 2.1. This makes the Bonanza record an extension of the Watson record.

Mass curve adjustment for precipitation data because of change in enviroment--Encroachment of shrubbery, trees, buildings, and other obstacles on the rain gage will influence in one way or another the amount of precipitation recorded, but just which way the record will be affected is uncertain. The suggestion has been made by other hydrologists that a mass diagram might reveal when such a change in surroundings had affected the catch. That is, a change might occur in the slope of the line representing the mass curve at a point where change of exposure had occurred Then a correction applied to each year's record in the part of the curve bent out of line would bring it back and make the total record more consistent with present day enviroment.

The method was applied to the 13-station data, but no improvements in precipitation runoff correlation resulted from the adjustment of records. A brief description is given here, however, with the thought that others may be interested in the procedure followed, or may be able to suggest other procedures. A mass diagram was prepared for each of the 13 precipitation stations. The October-April precipitation for each station was accumulated going back from 1945, with a subtotal taken for each year. This was plotted on the Y-axis, and the annually accumulated average October-April precipitation for the 13 stations was plotted on the X-axis. Thus the individual station eccentricities would be blended out in the 13 station average but its particular defection, if any, would be revealed by a change in slope of the mass curve line. If the station had been moved about the neighborhood through the years, the year of such change was spotted on the curve together with direction and distance in miles. Of 12 station moves recorded, only two concided with changes in slope of the line. One station was moved 12 miles with no visible effect on the mass curve. The mass diagram for Paonia, Colorado is shown on Figure 6, and that for Lay-Craig is shown on Figure 7.

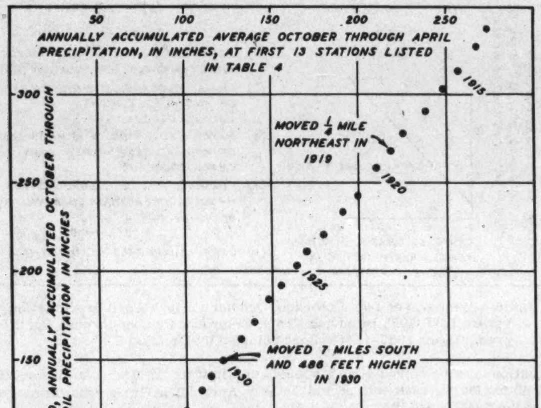

Fig. 6--Mass diagram of October through April precipitation at Paonia, Colorado

Data on changes of station location were obtained from the climatological office of the United States Weather Bureau in Denver, Colorado. Many of the data were in the form of maps, drawn to scale, showing the surrounding trees, shrubbery, and buildings as found in the 1941 inspection. Dates of erection of buildings are not recorded, but in three instances trees 20 to 40 feet high are located 15 to 20 feet from the gage. The gage in each instance has been located there long enough for the trees to grow, but no change is apparent in the slope of the mass curve line.

The acid test of the adjustment is the improvement, if any, when the adjusted precipitation is correlated with runoff. Only four of the 13 stations were affected. One station, Fraser, Colorado, had 17 of its 33 years changed. Table 6 shows results of adjusting these four stations. Two other stations showed an increase in correlation, two showed a decrease. The 13-station average was slightly reduced in its correlation with runoff when the adjusted precipitation was used, and therefore the method was of no value in this instance.

Table 6--Effect of adjustment in precipitation data on correlation with runoff at Grand Canyon

Station	Adjusted records		Unadjusted records	
	r	Standard error	r	Standard error
Crested Butte, Colorado	0.4664	± 0.141	0.6350	± 0.116
Durango, Colorado	0.5615	± 0.123	0.6714	± 0.099
Fraser, Colorado	0.5548	± 0.124	0.5016	± 0.134
Steamboat Springs, Colorado	0.6810	± 0.096	0.6550	± 0.102
13 Station Average	0.8756	± 0.042	0.8961	± 0.035

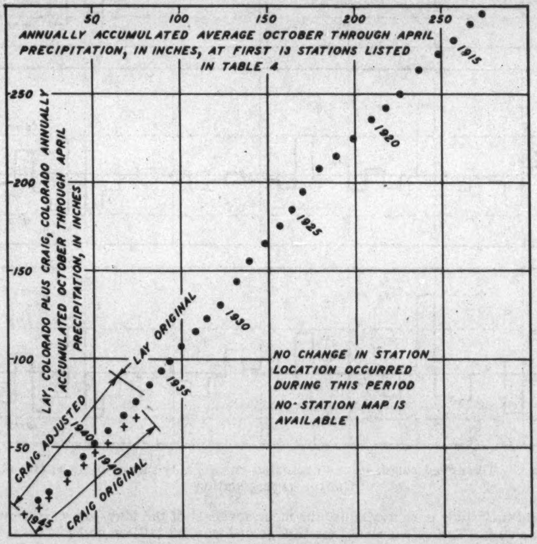

Fig. 7--Mass diagram of October through April precipitation at Lay, Colorado with Craig, Colorado added

Forecast formula for May 1 precipitation data--Correlation between the 13-station average October-April precipitation and May-July runoff gives an r of 0.896, and the regression equation, $Y = 1.68X - 5.45$. Y is the estimate of the May-July runoff in millions of ac ft. X is the average October through April precipitation in inches. A regression equation was also worked out for all station groups, and a computed runoff was ascertained for every year of the period 1913-1945. A chart of the observed runoff minus the computed runoff was plotted to ascertain how far the computed missed the observed through the years, and how many times it fell outside the various limits (see Fig. 6 for charts of the 13, 9, and 5 station groups). The pattern of all the charts was similar. The greatest discrepancy between observed and computed occurred in 1921. There it fell outside the 3σ limits for practically every group. Three times the standard error σ, is used as a measure of a purely fortuitous discrepancy. It may be exceeded about three times in a thousand without arousing suspicion. But when it occurs in a brief span of only 33 years and in every precipitation group between 4 and 26 stations, suspicion is justified that the discrepancy is more than fortuitous and is caused by an overt act peculiar to the 1921 record. Investigation revealed that the May-July runoff in 1921 was partially estimated. In United States Water Supply Paper 918 of the United States Geological Survey, Page 202, is Note b, relative to the 1921 record: "No discharge measurements were made at the Topock station between June 2 and July 15."

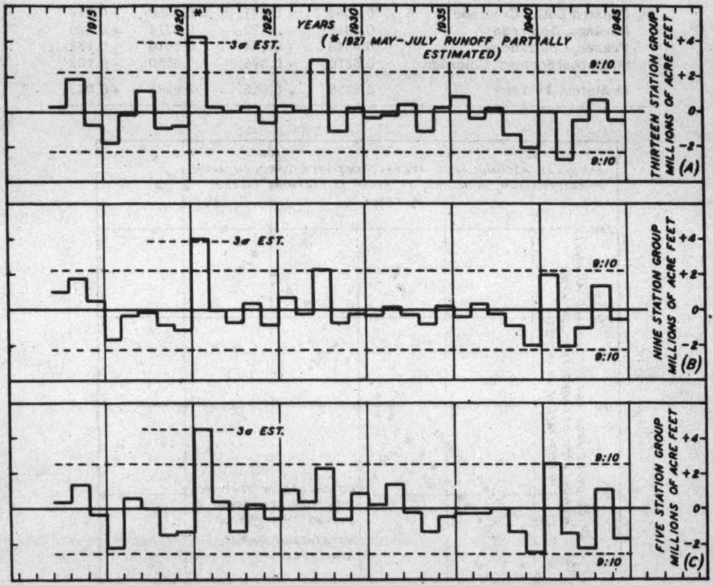

Fig. 8--Observed runoff minus computed runoff, May through July at Grand Canyon gaging station

In 1945, had this study been available, the mean forecast of the May-July runoff would have been 7.8 million ac ft. The actual runoff for this period was 7.3 million ac ft, 0.5 less than the mean of the forecast. Such success, however, would have been largely fortuitous. The best that can be said in advance of the occurrence of the runoff is that nine times in ten it will fall within about 2.3 million ac ft of the forecast mean. Figure 8A shows that three times in 33 years the difference (observed minus computed) went outside the 0.9 limits, or slightly less than one year in ten, which verifies the computation.

Maximum possible correlation--The question might be raised as to how much the correlation can be increased above 0.896 if the full October through July precipitation were known beforehand, instead of just the October-April amount. This of course is not available for a May 1 forecast, but a correlation using past data will tell what effect the total precipitation would have, if it were available.

Two correlations were made to test the idea. One used the October-July precipitation with May-July runoff. That yielded an $r = 0.911 \pm 0.03$ and a 0.9 prediction range of ± 2.12 million ac ft. In the other correlation the May-July precipitation was used as a third variable in a muliple correlation with October-April precipitation and May-July runoff. That yielded an $r = 0.916 \pm 0.03$ and a 0.9 prediction spread of ± 2.05 million ac ft.

Apparently then this method has been developed practically to the limit of its application because the forecast range could be reduced only 0.2 million ac ft from ± 2.3 to ± 2.1 if all the precipitation were known beforehand.

Another question immediately arises. Why a maximum possible correlation of only 0.916? The correlation of 0.916 does not mean that only 0.084 remains to obtain perfect and complete correlation. Rather, the factors yet to be discovered are represented by the coefficient of alienation $\sqrt{1 - r^2}$ or 0.40, which is a sizable figure. A large part of the difficulty must be laid to what is the as yet unknown missing link between precipitation and runoff.

The search should be continued, then, for another variable having a high correlation with runoff. Ideally, the missing variable should be independent of phenomena affecting and causing precipitation, so that the cross-correlation between precipitation and the missing variable would be low, because low cross-correlations accompanying high direct correlations usually result in high multiple correlations. If such a variable can be found, the forecasting problem will have reached a satisfactory solution.

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THE EFFECT OF ENTRANCE MIXING ON THE SIZE OF DENSITY CURRENTS IN SHAVER LAKE

Hugh Stevens Bell

Abstract--The present paper discusses entrance mixing and presents data that were obtained during June 1944, at Shaver Lake, California. We believe that no previous attempt has been made to study entrance mixing under field conditions.

Introduction--A density current is a gravity flow of a liquid or a gas through, under, or over a fluid of approximately equal density. Such currents may be differentiated, respectively, as interflows, underflow, and overflow. In 1943 Robert T. Knapp outlined and discussed briefly the mixing characteristics, of density currents in lakes and reservoirs [see "Reference" at end of paper, KNAPP, 1943]. After establishing two main categories, (1) localized mixing, and (2) general mixing, he subdivided the former into (a) entrance mixing, (b) plunge-point mixing, and (c) mixing due to channel irregularities. Physically, there is ample justification for these three subdivisions. Recent field experience, however, indicates that it is more convenient to treat plunge-point mixing as if it were merely the final stages of entrance mixing. Consequently, the term, "entrance mixing" as used herein includes plunge-point mixing.

Purpose of the investigation--When a stream enters a body of still water, mixing takes place between the inflowing and the impounded water. KNAPP [1943, pp. 294-295] points out that there is intense local mixing at the point of entrance, where large amounts of energy are made available through the shock losses involved in the change of momentum. The field studies at Shaver Lake were undertaken in order to learn at least the order of magnitude of entrance mixing.

Density currents normally follow the union of any stream with a body of still water. The specific gravity of the one is rarely, if ever, the same as that of the other, and although there are exceptions, any mixing of the two may be expected to produce a third mass of intermediate specific gravity. Under favorable conditions a current is possible when the specific gravity of the mixture varies as little as 0.01 per cent from that of the impounded water. This is approximately the difference between water at 69° and 70° F.

Shaver Lake--Shaver Lake is located about 40 miles northeast of Fresno, California. It lies at an elevation of 5370 feet, midway between Yosemite and Sequoia National Parks in the Sierra Nevada Mountains. The capacity is about 135,000 acre feet. It is the largest of the three main storage reservoirs of the Big Creek-San Joaquin River hydro-electric development of the Southern California Edison Company. Runoff from the immediate watershed is of little importance. The principal inflow occurs during May, June, and July, when approximately 115,000 acre feet are diverted from Huntington Lake and Pitman Creek. This water flows through a tunnel to a point some three miles from Shaver Lake and 1300 feet higher. There it enters the North Fork of Stevenson Creek, known locally as Tunnel Creek, and continues down a steep, rocky, natural channel until it reaches the Lake.

Shaver Lake was chosen as the site for the field studies because this inflow, which is measured and controlled to a considerable degree, is invariably colder than the surface stratum of the Lake. This practically guarantees subsurface density currents. Furthermore, conditions remain surprisingly stable for long periods. For instance, from $18^{h}00^{m}$ on June 1, 1944, until $14^{h}00^{m}$ on June 14, 1944, the temperature of the Tunnel Creek discharge was never less than 9.°8 or more than 13.°5 F colder than the surface stratum in the reservoir. The mean temperature difference was 11.°8 F, and the mean difference in specific gravity was not quite 0.001. During that same period the discharge varied from 1100 cfs to 1250 cfs. The maximum fluctuation in 24 hours was only 90 cfs. The entrance velocity was roughly 12 fps. The water was so remarkably free from suspended sediment and dissolved minerals that specific-gravity determinations of sufficient accuracy could be made solely upon the basis of temperature.

Tunnel Creek and a small, apparently nameless stream, enter the reservoir in a bay which, at spillway level, has a surface area of about 20 acres and a capacity of some 500 or 600 acre feet.

Although the small stream discharges as much as 20 cfs late in May, this dwindles to less than five cfs by the end of June. Because this flow was always less than two per cent, usually nearer one per cent, of that from Tunnel Creek, it has been neglected in making calculations.

The zone of entrance mixing lies within the small bay. The most useful data were obtained on a cross section (C C) established some 1600 feet from the mouth of Tunnel Creek, just outside the moderately restricted entrance to the bay. The locations of this and the three other cross sections shown in Figure 1 were determined before going into the field by constructing a 1:400 model of the upper portion of the reservoir basin. Dyes made it easy to observe the paths taken by laboratory density currents. In the field they had to be hunted with current meters and thermometers, but their favorite routes were known from the model studies.

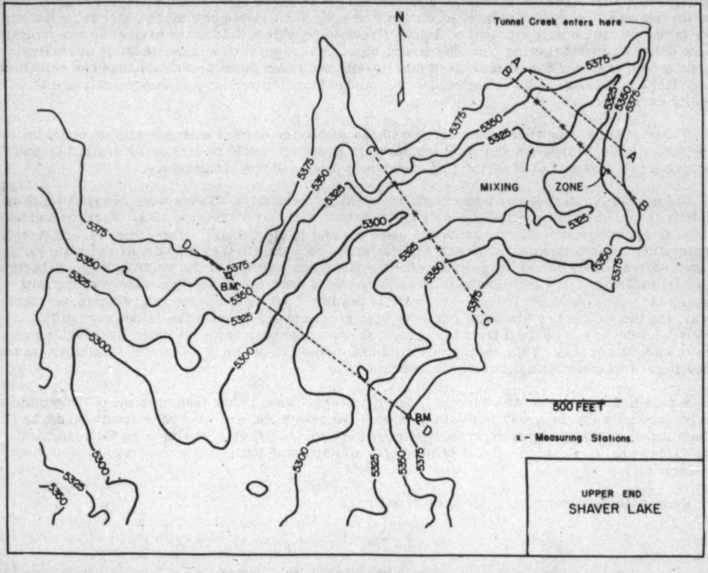

Fig. 1--Contour map of the upper end of Shaver Lake showing the four cross sections at which observations were made and the location of measuring stations mentioned in the text

A boat could be positioned nicely on any cross section with the aid of pairs of markers that were set on opposite shores. Exact positions were located with an alidade on a base map supplied by the Southern California Edison Company, whose fine cooperation before, during, and after the field investigation did much to assure success. The water was from 50 to 70 feet deep at mid-channel and three or even four anchors were needed occasionally to keep the boat on station.

Methods of approach--The physical conditions at Shaver Lake offer two rather obvious opportunities for evaluating entrance mixing. (1) Reservoir water that is mixed with that of Tunnel Creek flows downstream as part of a density current and must be replaced. In the Lake this gives rise to upstream currents whose combined flow represents approximately the mixing demand, that is, the quantity of stored water per unit time consumed by entrance mixing. Therefore, if the flow of these upstream currents can be determined, the problem is solved. (2) If the flow of the downstream density current czn be ascertained, the mixing demand can then be established by subtracting from it the known inflow from Tunnel Creek.

Assuming that sufficiently accurate data are obtainable, either method offers a very straightforward solution of the problem. They require merely the determination of the flow of one or more currents within the reservoir and the readily available discharge data for Tunnel Creek. Good data on the reservoir currents were difficult to obtain because velocities in the Lake never exceeded 0.8 fps, and at most of the stations rarely reached 0.5 fps. The current meter, therefore, had to be used almost always in its least dependable range. Under such circumstances bobbing and drifting may become sources of serious error. To mininize this a heavy boat was used with several anchors.

Before the field work was begun, a third approach, based largely upon temperature measurements, seemed to offer a method requiring a minimum of data and a single simple calculation. It was reasoned that since the discharge of Tunnel Creek could be learned from stage-recorder data, and its temperature readily measured, it would be easy to calculate how much water from the surface layer must be mixed with that of Tunnel Creek to provide a fluid mass having the temperature of the density current flowing from the mixing area. This approach was particularly attractive because temperatures can be measured more easily and much more accurately than can velocities under field conditions. This is especially true when velocities are low, as they usually are in density currents.

Three assumptions were made: (1) The impounded water used in entrance mixing would be supplied by a single layer in which (2) temperature gradients would be lacking or negligible and (3) the current flowing out of the mixing area would be of uniform temperature.

Unfortunately, all three of these basic assumptions were false. There were always two, occasionally three, upstream currents supplying reservoir water to the mixing zone. Vertical and horizontal temperature and velocity gradients were present in all of them. Under such circumstances temperature measurements, no matter how numerous or accurate they may be, are of little value in themselves. They permit us to determine the mean temperature of the water *in* a cross-section at a particular time, but the third method requires us to know the mean temperature of the flow *through* the cross-section. If there are velocity gradients but no temperature gradients, or vice versa, the two values are identical, but when both gradients are present the values may differ widely because one is derived from temperatures and areas only while the other takes velocities into consideration also. This means that the third method as originally conceived could not be used, since it gave no consideration whatever to velocities.

A modified form of the third method, based upon heat flow rather than upon mean temperature, can be used because the necessary data on areas, temperatures, and velocities are at hand. Although it makes use of highly dependable temperature measurements, it also uses the less accurate velocity data. Consequently, it fails to give a simple and independent solution of the mixing problem.

Expressed mathematically, Methods 1 and 2 are

$$Q_m = Q_- \quad \text{(1)}$$

$$Q_m = Q_+ - Q_c \quad \text{(2)}$$

where Q_m is the rate at which impounded water is mixed with the inflow, Q_+ is the total rate of flow downstream in the Lake, Q_- is the upstream flow in the Lake, and Q_c is the flow into the Lake. At Shaver Lake, Q_- was composed of a surface flow, Q_s, and an underflow, Q_u. In the calculations Q_- has been replaced by the sum of these two flows. The downstream flow was an interflow and, for clarity, is represented by Q_i rather than Q_+ as above.

The expressions for Method 3 may be derived by equating the heat flow into the mixing zone to that out of the zone,

$$\Sigma w\gamma \Delta Q_- T_- \Sigma w\gamma \Delta Q_c T_c = \Sigma w\gamma \Delta Q_+ T_+$$

where the Q terms are elements of flow in the respective streams, T represents the temperature of the elements, w is the specific weight of water, γ is the specific heat value for water, and Σ denotes summation over the cross-section of each stream. Each term can be evaluated numerically from the measured data. The numerical result will be the quantity of heat flow per unit time. The first term will become

$$\Sigma w\gamma \Delta Q_- T_- = w\gamma Q_- \overline{T}$$

where, by definition, $\bar{\bar{T}}_-$ is the average temperature in the upstream flow, Q_-, in the Lake. The heat-flow equation now becomes

$$w\gamma Q_-\bar{\bar{T}}_- + w\gamma Q_c\bar{T}_c = w\gamma Q_1\bar{T}_1 = w\gamma(Q_s + Q_u + Q_c)\bar{T}_1$$

and the mixing rate is

$$Q_m = Q_- = Q_s + Q_u = (Q_s\bar{T}_s + Q_u\bar{T}_u + Q_c\bar{T}_c)/\bar{T}_1 - Q_c$$

Equipment--Temperature measurements in Tunnel Creek and at the Lake surface were made with a solid-stem thermometer graduated in tenths of a degree Centigrade; temperatures below the surface were obtained by using a bathythermograph (an instrument that records temperatures against depth) and a reversing thermometer which could be read with ease to the nearest tenth-degree Centigrade. Velocities were determined with a Price current meter which had been rated to 0.05 fps by the National Bureau of Standards. Depths were measured to the nearest tenth of a foot for all instruments by means of revolution counters on the hoisting reels. Wind velocities were estimated.

The direction in which currents flowed was determined by observing, with the aid of a glass-bottomed box, either the current-meter weight or the highly polished fins on the current meter. The fins were visible to depths of about 45 feet. Directions for currents at greater depths were assumed after studying temperature and velocity data. This was not too difficult, because at the only station were the problem was encountered, the topography was such that in the greater part of the area where direct observation was not possible the flow virtually had to be normal to the cross-section, as indicated by Figures 1 and 3. It was necessary, therefore, only to decide whether it was upstream or downstream.

Presentation of data--On June 6 and 7, 1944, measurements were made of temperatures and velocities at four stations on cross section CC. This location was immediately downstream from the point at which inflows of 1000 to 1250 cfs appeared to plunge beneath the surface.

Data for these two days are combined because they supplement each other even though those for neither day are adequate for the flow through the cross-section to be calculated. This treatment seems permissible because of the similarity of conditions on the two days. Inflow from Tunnel Creek fluctuated between 1115 and 1160 cfs, and the mean was 1138 cfs. At Shaver Dam the maximum and minimum air temperatures were 71° and 47° F on June 6, 72° and 48° on June 7.

Measurements made at a vertical located at the center, that is, at the point where the water was deepest, show that there were three distinct currents flowing through the cross-section: (1) A surface current from four to six feet deep, upstream and normal to the cross-section; (2) an interflow about 37 feet deep, downstream and passing through the section at an angle of approximately 65°; (3) an underflow about 24 feet deep, upstream and normal to the cross-section. Figure 2 is a schematic presentation of the circulation pattern within the mixing zone and shows velocity and temperature profiles for the several currents at the center of cross-section CC, The upper two currents were detected also at stations located on the same cross-section 185 feet

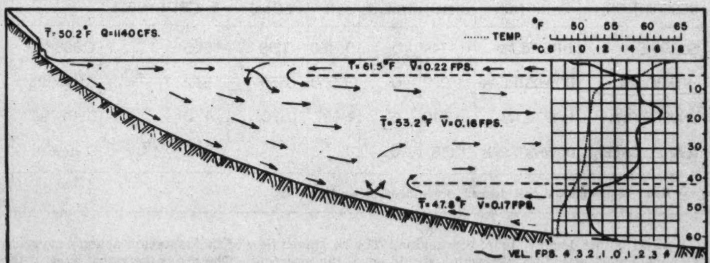

Fig. 2--Schematic presentation of flow in mixing zone with accompanying velocity and temperature profiles at center of cross-section CC, Shaver Lake, June 6 and 7, 1944 to the north and 155 feet to the south of the center. Only the surface current could be identified at a station 235 feet south of the center. At the most northerly station it was not over two feet thick as compared with more than seven feet at the southermost station. The difference in thickness is probably due to the fact that the interflow tends to "pile up" on the north shore, by which it is forced to alter its course. The wedgelike cross section of the surface layer is shown in Figure 3, the primary purpose of which is to show the locations of the four stations on cross section CC, the temperature and velocity distributions at each, and the velocity contours of the interflow.

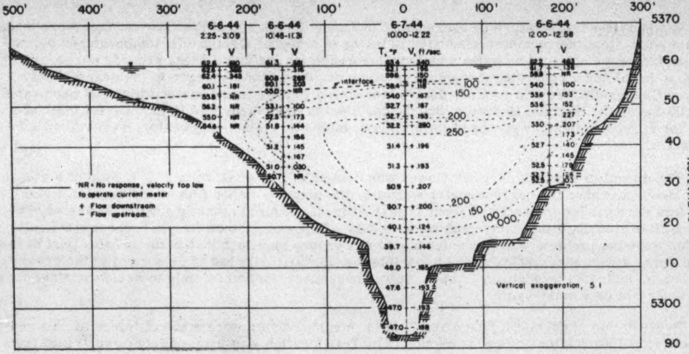
500'
400'
300'
200'
100'
0
100'
200'
300'
6-6-44
2:25-3:09
6-6-44
10:45-11:31
6-7-44
10.00-12.22
6-6-44
12.00-12.58
T
V
T, °F
V, ft/sec.
interface
100
150
200
250
000
NR = No response, velocity too low to operate current meter
+ Flow downstream
− Flow upstream
Vertical exaggeration, 5.1
5370
60
50
40
30
20
10
5300
90
ELEVATION

Fig. 3--Diagram of cross-section CC showing velocities and temperatures on four verticals, and indicating velocity contours for interflow, Shaver Lake, June 6 and 7, 1944

Table 1 gives all data needed to calculate the magnitude of entrance mixing by the methods outlined. The equations for calculating Q_m, the rate at which mixing occurs, and $\overline{T}_i$, the mean temperature of the interflow, are given with numerical results in Table 2. Apparently the impounded water used in entrance mixing was equal to from 75 per cent to 96 per cent of the discharge of Tunnel Creek. In other words, the interflow had a volume roughly twice as great as that of Tunnel Creek.

Table 1--Summary of data, section CC, June 6 and 7, 1944

CURRENT		DISCHARGE		AREA	MEAN VELOCITY	MEAN TEMPERATURE		SPECIFIC GRAVITY
DESCRIPTION	DIRECTION	Q(cfs)	SYMBOL	sq.ft.	V (fps)	$\overline{T}^a$ (°F)	SYMBOL	
SURFACE	UPSTREAM	744	Q_s	3 460	0.215	61.5	$\overline{T}_s$	0.998882
INTERFLOW	DOWNSTREAM	1 989	Q_i	13 900	0.159	53.2	$\overline{T}_i$	0.999523
UNDERFLOW	UPSTREAM	340	Q_u	1 997	0.170	47.8	$\overline{T}_u$	0.999796
TUNNEL CREEK	DOWNSTREAM	1 138	Q_c			50.2	$\overline{T}_c$	0.999691

[a] Mean temperatures are derived from heat-flow data.

Several points deserve brief discussion. The combined flow of the upstream density currents and Tunnel Creek was 2222 cfs, which should equal the interflow. The cross sectional area of the latter, when multiplied by its mean velocity, indicates a flow of 2210 cfs. This nearly perfect agreement vanishes when account is taken of the angle at which the current passes through the cross section. With this correction Q_i becomes 1989 cfs.

Table 2--Data on entrance mixing and interflow temperature, section CC, June 6, 7, 8, 1944

ENTRANCE MIXING			INTERFLOW MEAN TEMP.	
HOW OBTAINED	MIXING RATE Q_m (cfs)	MIXING RATIO Q_m/Q_c	HOW OBTAINED	T_i (°F)
	USING DATA FROM TABLE 1			
EQ(1a) $Q_s + Q_u = Q_m$	1084	0.96	EQ(3a) $\frac{Q_sT_s + Q_uT_u + Q_cT_c}{Q_s + Q_u + Q_c} = T_i$	53.6
EQ(2a) $Q_i - Q_c = Q_m$	851	0.75	GRAPHICAL INTEGRATION	53.2
	USING ADJUSTED VALUES OF Q_s & Q_u			
Q_m ASSUMED SEE TEXT	851	0.75	EQ.(3a)	53.2
EQ(1a) AFTER SOLVING EQ.(3a) FOR Q_s	973	0.85	ASSUMED	53.2

Equation (2a) of Table 2 makes use of very satisfactory discharge data for Tunnel Creek, and interflow data which are the most abundant and probably the most dependable obtained for any of the reservoir currents. According to it the mixing rate, Q_m, is 851 cfs. But $Q_s + Q_u = Q_m$, which, as Table 2 shows, is 1084 cfs. The latter value of Q_m is more than 28 per cent greater than the former. Because of the better quality of the data used in Equation (2), the smaller value is more acceptable.

The top portion of the righthand section of Table 2 shows that a mean temperature of 53°.6 F would be obtained by combining the discharges of the upstream reservoir currents with that of Tunnel Creek. A graphical integration of the interflow data indicates only 53°.2 F. In view of the difference in the rate of mixing as calculated by equation (1a) and (2a) this close agreement is surprising. T_i apparently is not a very sensitive index of entrance mixing.

Granted field data and methods of calculation that are flawless, the values of Q_m should be nearly identical whether they are found by (1a) or (2a). So also should the values of $\overline{T}_i$ whether they are determined by graphical integration of heat-flow measurements of the interflow, or by (3a).

Equation (3a) is convenient for trying out various assumptions and see how they will affect Q_m and $\overline{T}_i$. Since temperature data are probably more accurate than discharge data, let it be assumed that the values of $\overline{T}$ as shown in Table 1 are correct, that the tabulated values of Q_i and Q_c are also correct, but that $Q_s + Q_u$ is 851 cfs as indicated by (2a). The ratio Q_s/Q_u, by Table 1, is 744/340. If Q_s is adjusted to 584 cfs and Q_u to 267 cfs their total is 851 cfs and their ratio is as 744/340. When these new values are substituted in (3a), $\overline{T}_i$ becomes 53°.2, which is identical with the value derived from a graphical integration of the completely independent data for the interflow.

Several factors conspire to make Q_s the least dependable value in Table 1. If it is assumed, then, that all other values in that Table are correct, and (3a) is solved for Q_s, the answer is 633 cfs and Q_m becomes 973 cfs. This indicates a mixing rate falling nearly midway between those determined by the other methods. The lower half of Table 2 shows the influence of various adjustments on Q_m and $\overline{T}_i$.

The differences in specific gravity were very small, as may be seen in the final column of Table 1. Between the water of Tunnel Creek and that of the surface current the difference was 0.0008, but between Tunnel Creek and the underflow it was only 0.0001. For the sake of comparison, one ounce of sediment suspended in a cubic foot of water increases the specific gravity 0.0006, and the difference between the specific gravity of sea water and fresh water is about 0.025.

June 28, 1944--Figure 4 presents velocity and temperature profiles for June 28, 1944, at four stations on cross section CC, and Tables 3 and 4 provide a summary of the data. The discharge of Tunnel Creek was 625 cfs as compared with about 1140 cfs on June 6 and 7, 1944.

Table 3--Summary of data, section CC, June 28, 1944

CURRENT		DISCHARGE		AREA	MEAN VELOCITY	MEAN TEMPERATURE		SPECIFIC GRAVITY
DESCRIPTION	DIRECTION	Q(cfs)	SYMBOL	sq. ft	V(fps)	$\overline{T}$[a] (°F)	SYMBOL	
SURFACE	UPSTREAM	336	Q_s	4 800	0.07	65.5	$\overline{T}_s$	0.998482
INTERFLOW	DOWNSTREAM	1 482	Q_i	14 970	0.11	57.2	$\overline{T}_i$	0.999244
LOWINTERFLOW	UPSTREAM	285	Q_u	3 800	0.075	51.6	T_u	0.999615
UNDERFLOW	UPSTREAM	32	Q_u	900	0.035	48.6	$\overline{T}_u$	0.999766
TUNNEL CREEK	DOWNSTREAM	625	Q_c			54.8	$\overline{T}_c$	0.999421

[a] Mean temperatures are derived from heat-flow data.

Table 4--Data on entrance mixing and interflow temperature, section CC, June 18, 1944

ENTRANCE MIXING			INTERFLOW MEAN TEMP.	
HOW OBTAINED	MIXING RATE Q_m(cfs)	MIXING RATIO Q_m/Q_c	HOW OBTAINED	$\overline{T}$ (°F)
	USING DATA FROM TABLE 3			
EQ.(1a) $Q_s + Q_u = Q_m$	653	1.02	EQ(3a) $\frac{Q_s\overline{T}_s + Q_u\overline{T}_u + Q_c\overline{T}_c}{Q_s + Q_u + Q_c} = T_i$	56.79
EQ.(2a) $Q_i - Q_c = Q_m$	857	1.37	GRAPHICAL INTEGRATION	57.20
	USING ADJUSTED VALUES OF Q_s & Q_u			
Q_m ASSUMED: SEE TEXT	857	1.37	EQ. (3a)	56.90
EQ(1a) AFTER SOLVING EQ(3a) FOR Q_s	609	0.98	ASSUMED	56.84
DITTO	722	1.16	ASSUMED	57.20

As calculated from interflow data Q_i was 1482 cfs, which is 204 cfs greater than the total flow into the mixing zone as shown in Table 3. Prorating this additional flow to the three upstream currents increases Q_s to 440 cfs, the low interflow to 375 cfs, and the underflow to 42 cfs. A homogeneous mixture of these flows with that of Tunnel Creek would have a temperature of 56°.8 F. This agrees fairly well with the 57°.2 figure obtained by graphical integration of velocity and temperature measurements made within the interflow.

Q_s was found to be 292 cfs by (3a) when $\overline{\overline{T}}_i$ was assumed to be 56°.84 F, the average of the values obtained for $\overline{T}_i$ by (3a), and all other values were taken from Table 3. This is to be compared with 336 cfs from field measurements and 440 cfs by proration as described in the preceding paragraph. These are reasonable variations in view of the exceptionally complex flow pattern prevailing in the

upper 15 feet of the cross section. The surface current decreased in velocity with depth and across the section from north to south. It varied in thickness from less than two feet to more than four feet. Beneath it there was a layer some ten to 13 feet thick in which velocities varied from 0.0 to 0.1 fps and the flow was literally in all directions, being upstream, downstream and more or less parallel to the cross section, depending upon depth and station.

The complexity of the flow at all stations and all depths is indicated by the velocity profiles in Figure 4. It should be noted that at three of the stations the downstream flow increased in velocity with depth, then fell off only to increase again almost to the previous maxima before returning to zero. At the two stations where the water was more than 55 feet deep there were two fairly pronounced maxima in the current or currents flowing upstream beneath the interflow. A study of the profiles for these two stations shows that at one there were apparently five and at the other there were possibly seven fairly distinct currents rather than the usual three.

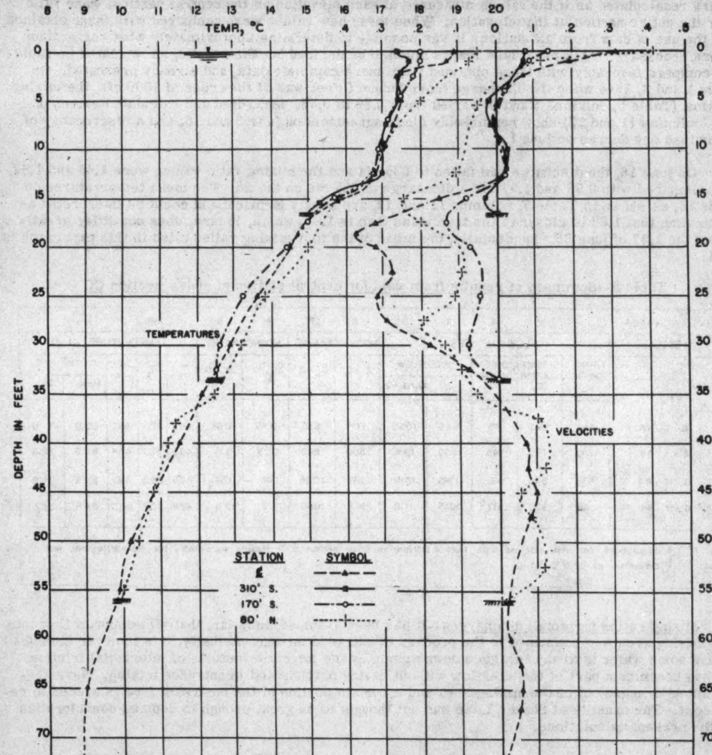

Fig. 4--Temperature and velocity profiles for four stations on cross section CC, June 28, 1944

Table 4 shows that the interflow was from 98 per cent to 137 per cent greater than Tunnel Creek, as compared with 75 per cent to 96 per cent on June 6 and 7, 1944. On June 28 the difference in specific gravity between the water of Tunnel Creek and that of the two reservoir currents with which it mixed were 0.009 and 0.002 as compared with 0.008 and 0.001 previously. If (2a) is used to find the magnitude of entrance mixing on each occasion, the figure is 851 cfs for the first, and 857 cfs for the other even though the discharge of Tunnel Creek had decreased to only 55 per cent of its former vlaue. Why small flows may mix more efficiently than large ones will be discussed after the presentation of other data.

June 1, 3, and 16, 1944--On June 1, 3, and 16, data were taken at the center of cross section CC but not elsewhere. Although these data alone are inadequate for calculating the mixing demand on those days, a procedure has been developed that permits estimates to be based upon them. For those days on which fairly complete data were obtained, the flows through the cross section were recalculated as if the values measured at each elevation on the central vertical were valid for the entire section at that elevation. When these new values were compared with those obtained by the use of data from all stations it was possible to determine approximately what corrections were necessary. This procedure leaves much to be desired but the results, as tabulated in Table 5, compare favorably with those obtained from more complete data, and already presented. On June 1 and 3, 1944 when the discharge from Tunnel Creek was of the order of 1000 cfs, the mixing ratios (Table 5, columns 8 and 9) varied from 0.68 to 0.76. Measured and calculated values of $\overline{T}_1$ (columns 11 and 12) show remarkably close agreement on June 3 and 16, and a discrepancy of less than one degree on June 1.

On June 16, the discharge had fallen to 635 cfs and the mixing ratio values were 1.46 and 1.68, as compared with 0.98 and 1.37 for a discharge of 625 cfs on the 28. The mean temperatures on June 16, as shown in Table 5, columns 11 and 12, are nearly identical and could be interpreted as indicating that 1.68 is closer to the true value than is 1.46, which, in turn, does not differ greatly from the 1.37 of June 28. Incidentally, the mean of the four mixing ratios cited in this paragraph is 1.37.

Table 5--Summary of results from data for central station of cross section CC

COLUMN NUMBER	1	2	3	4	5	6	7	8	9	10			11	12
DATE	FLOW IN CFS					MIXING DEMAND		MIXING RATIO		TEMPERATURE IN °F				
	TUNNEL CREEK Q_c	SURFACE CURRENT Q_s	UNDER-FLOW Q_u	INTERFLOW		$Q_i - Q_c$	$Q_s + Q_u$	$\frac{Q_i - Q_u}{Q_c}$	$\frac{Q_s + Q_u}{Q_c}$	T_c	T_s	T_u	T_i	
				Q_i	$Q_c+Q_s+Q_u$								Meas.	Calc.
6 - 1 - 44	940	580	75	1649	1595	709	655	0.75	0.68	48.2	58.1	48.0	50.9	51.8
6 - 3 - 44	1100	795	45	1900	1940	800	840	0.73	0.76	48.0	57.7	48.4	51.9	52.0
6 - 16 - 44	635	845	161	1565	1641	930	1006	1.46	1.68	46.8	56.3	49.1	51.9	51.8
[a] 6 - 17 - 44	68	933	117[b]	1036	1118	968	1050	14.2	15.5	47.8	57.7	50.0	54.8	56.5

[a] Calculations for this date use data from 4 stations on Cross-section B-B. Results are probably not dependable; see text.
[b] Estimated as 12.5 % of Q_s.

Mixing ratios for small discharges--It has been assumed, thus far, that all upstream flow into the mixing area was consumed in the process of entrance mixing. Actually, this is never true because some water is always dragged downstream by the interflow because of interfacial friction. It thus becomes a part of the interflow without having participated in entrance mixing. Nevertheless it is dragged out of the mixing area and a certain portion of the upstream flow is needed to replace it. The quantity at Shaver Lake was not thought to be great enough to demand consideration in the present calculations.

When the discharge from Tunnel Creek was greater than 500 cfs, the assumption that all upstream flow was the result of entrance mixing was probably essentially valid, but for small flows it very definitely was not. Just as the interflow drags water along by interfacial friction, so also a breeze drags the surface layer of the reservoir. At Shaver Lake this breeze was upstream throughout the hours when data were being taken. When discharges from Tunnel Creek were small the quantity of water dragged upstream by the wind may have greatly exceeded the mixing demand.

On June 17, 1944, the flow in Tunnel Creek had dropped to 68 cfs from 635 cfs on the previous day. The interflow moved through cross section CC at velocities too low to actuate the current meter. Consequently, data were taken at four stations on cross section B-B, located about 650 feet from the mouth of Tunnel Creek. Even at this comparatively favorable location no velocity data were obtainable in the area below the interflow. When the usual treatment was applied to the data from cross section BB the indicated mixing ratios were 14.2 and 15.5. Table 5, columns 6 and 7, shows that the mixing demand was as great as might have been expected for discharges in excess of 1000 cfs. There was unusually close agreement between measured and calculated values of Q_i, as shown by columns 4 and 5, but the difference between $\overline{T}_i$ by integration and by (3a), as shown in columns 11 and 12, was about twice as great as that shown by any other set of data presented here. Interflows of the size indicated could not have escaped detection at cross section CC, but repeated attempts at that location failed to show velocities high enough to run the current meter. There are, therefore, several reasons for doubting the validity of mixing ratios as high as 14 or 15 for June 17.

For several weeks the discharge of Tunnel Creek had been greater than 600 cfs. During that time two great eddies developed and persisted in the mixing zone, rotating in opposite directions about vertical axes like a pair of meshed gears. Several hundred acre feet of water were involved in this circulation pattern. During the afternoon of June 16 the discharge of Tunnel Creek decreased rapidly from 635 cfs to about 70 cfs. It seems entirely possible that the established circulation pattern continued during the period when data were being taken on the following day. If so, it could result in the movement of considerable quantities of water upstream through cross section BB, which was located in the upstream half of the eddy area. The fact that eddy circulation of this kind was not observed and does not seem to be indicated by the data could be a result of the selection of measuring stations at locations where only the upstream flow of these eddies was encountered, with the corresponding downstream flow occurring between stations. Under these circumstances the indicated mixing ratio could be very much greater than the actual one.

Re-examination of the data shows that there were no interfaces of the usual kind at which are found sharp breaks in the temperature gradient and a sudden reversal in the direction of flow. However, at depths of from 12.5 feet to 20 feet, depending upon the vertical at which measurements were made, there was an area of nearly motionless water above which there was no downstream flow and below which there was no upstream flow of sufficient strength to register on the current meter. This dividing line coincided conspicuously with the 56° F temperature contour.

The steepest part of the temperature gradient was found several feet below the 56° F contour. Immediately above and below this break measurable velocities were found in what may have been two distinct downstream currents. Perhaps the upper one contained the excess from the surface flow that had been blown into the area and, possibly, the lower one was a true density current produced by entrance mixing. The latter current was bounded by the 52°.5 and the 50°.5 contours, had a mean temperature of 51°.8 F and a flow of 385 cfs. If it is assumed that it contained all the flow from Tunnel Creek, mixed with 317 cfs of stored water, the mixing ratio was 4.67. $\overline{T}_s$ was 57°.8, $\overline{T}_u$ was 50°.0 and $\overline{T}_c$ was 47°.8. If the 68 cfs from Tunnel Creek were mixed with 106 cfs from the surface current and 211 cfs from the underflow, the resulting interflow would have a volume of 385 cfs and a mean temperature of 51°.8. This combination fits the field data for the interflow exactly. The temperature of Tunnel Creek was such that mixing with water from the lower levels would be easier than with water from the surface because of the smaller difference in specific gravity. Between the surface current and Tunnel Creek the difference in specific gravity was 0.00061, but when the mixture of these two reached the lower mass of water the difference was less than one-third as great, 0.00019. This makes the admixing of an unusually high percentage of water from the lower levels, as suggested above, seem likely.

Factors governing the mixing ratio--There is a consistent trend in the Shaver Lake data indicating that the mixing ratio is influenced principally by three variables: (1) Difference in specific gravity; (2) the available specific energy; and (3) the hydraulic radius. This is not the conventional hydraulic radius obtained by dividing the cross-sectional area by the wetted perimeter but a special one in which the cross-sectional area is divided by that portion of the perimeter which is in contact with other fluid masses. It is only the interfacial portions of the perimeter that are considered. For underflows and overflows this portion is usually less than 50 per cent, but for interflows it ordinarily is greater and often is the entire perimeter.

In general, any increase in the difference in specific gravity or in the hydraulic radius tends to decrease mixing whereas any increase in specific evergy tends to increase it.

The difference in specific gravity is important primarily because it determines to what extent gravity may be effective in preventing the mixing of adjacent fluid masses. It is not too obvious that the cold water at the bottom of a lake is being buoyed up by the warmer water above it, or that the lake itself is being buoyed by the overlying atmosphere. All of us realize, however, that less energy is expended when we lift a bucket of water from the bottom of a well to the surface of the water in the well than when we lift that same mass an equal distance through the air. On the one hand gravity is almost completely offset by buoyancy, but on the other the buoyancy is so small as to be negligible. Since mixing involves moving fluid masses, it follows that, other things being equal, the more nearly alike the specific gravities of the fluids to be mixed, the more readily they will mix because the stabilizing influence of gravity is less effective.

The effective gravity, g_e, may be determined readily from the equation $g_e = g(s - s')/s$, where g is the normal gravitational acceleration, s the specific gravity of the heavier fluid, and s' the specific gravity of the lighter one. At no time during the field investigations at Shaver Lake was g_e as great as 0.032 ft/sec^2, and often it was little more than 0.003 ft/sec^2. It should be noted that this latter figure is roughly 0.0001 of the normal value of gravity. The very fact that there were density currents is proof that gravity forces of even these small values are not entirely negligible. It seems inprobable, however, that such variations as there were in g_e were important causes of the observed differences in the mixing ratio.

The statement that any increase in the available specific energy tends to increase mixing is not one that can be proved by the data from Shaver Lake. Slopes near the mouth of Tunnel Creek are so steep that the discharge is white with entrained air when it enters the lake, as Figure 5 shows clearly. The entrance velocity apparently remained nearly constant at about 12 fps regardless of the discharge, according to estimates made by using floats under unusually difficult circumstances. Velocities probably were slightly higher for the larger discharges and, if so, there must have been some increase in the available specific energy. Nevertheless, the mixing ratio decreased consistently as the discharge increased.

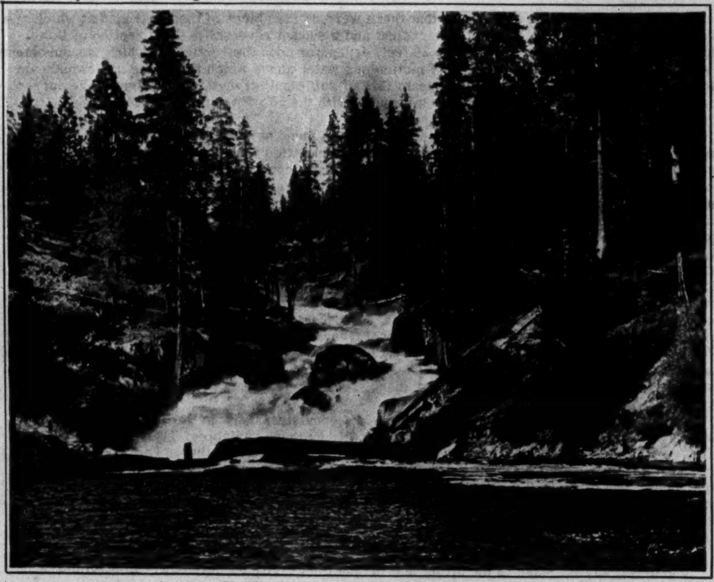

Fig. 5--Tunnel Creek as it enters Shaver Lake

By process of elimination it must be concluded that the third factor, the hydraulic radius, accounts for the observed variations in the mixing ratio. Obviously it is impossible to mix two fluid masses, regardless of the energy available, unless they can be brought into direct contact with each other. Obviously, also, the greater the area of contact per unit volume the greater the opportunity for mixing. Fundamentally, it is a problem of specific surface. If the geometry of the flow remains constant, the area of contact per unit volume increases at an ever accelerating rate as the size decreases.

Flattening of the cross section decreases the hydraulic radius. Both interflows and overflows usually become thin because of the remoteness of channel walls. The hydraulic radius may be small, then, either because of the size or the shape of the croos section. In large, thick flows, much of the energy that could cause mixing is buried in the depths of the mass where it is dissipated in ineffective stirring, but small and thin flows are much more efficient mixers because a higher percentage of the available energy is near the boundary through which mixing must take place.

Undoubtedly, the interflows at Shaver Lake were proportionally thinner for small discharges than for large ones. With both size and shape combining to reduce the hydraulic radius, very small discharges like that of June 17, 1944, resulted in higher mixing ratios.

Summary and conclusions--Entrance mixing produced thermal density currents at Shaver Lake that were from less than twice to nearly five times the size of the inflowing streams. The hydraulic radius, the difference in specific gravity, and the available specific energy are the chief factors influencing entrance mixing. Small inflows tend to mix more readily than large ones. At Shaver Lake, entrance mixing did not quite double the volume of flows of 1000 cfs, more than doubled those of approximately 600 cfs, and may have increased those of less than 100 cfs by as much as five-fold. A twenty-fold range in the discharge of Tunnel Creek is believed to have produced a seven-fold range in the mixing ratio.

Differences between the specific gravity of the inflowing and the impounded water were extremely small, and inflow velocities were high in comparison with those to be expected for the Colorado River at Lake Mead and for the Rio Grande at Elephant Butte Reservoir. It seems probable, therefore, that the mixing ratio at Shaver Lake is somewhat higher than can be expected in reservoirs where turbid density currents make entrance mixing an important consideration reservoir operation.

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CRUSTAL STRUCTURE AND SURFACE HEAT FLOW NEAR THE COLORADO FRONT RANGE

Francis Birch

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Abstract--Two important assumptions regarding the Earth's crust are widely accepted: (1) That in the process of mountain formation, the crustal layers are thickened with the development of "roots" sufficiently great to compensate approximately the visible inequalities of elevation; (2) that most, if not all, of the radioactive production of heat takes place in the upper layers by virtue of average concentrations of radioactive elements comparable with those found in laboratory samples. If these two assumptions are correct, we may expect to find an increased surface heat flow in and near mountainous or plateau regions. The magnitude of the effect to be expected is computed for various sizes of root, distributions of heat production, and intervals since thickening. The analytical results are compared with certain preliminary studies of heat flow along the Colorado Front Range. It is concluded, tentatively, that the more extreme forms of upward concentration of heat production are improbable; but the present data are inadequate for a completely satisfying answer. The bearing of other possible measurements on this problem is briefly discussed.

The work which I propose to describe is really a preliminary stage in a program of research, and there are few definite conclusions at the present time. I have chosen to present this topic in its incomplete form with the hope that others may become interested in these problems and also that opportunities for further measurements may be called to my attention.

I have attempted to follow out quantitatively the thermal consequences of a set of ideas which, taken together, comprise a rather large fraction of modern geophysical doctrine. I believe that in a general way, with some disagreement as to details, most geophysicists will assent to the following propositions: (1) The "normal" continental crust, distant from present mountainous regions, may be described approximately in terms of several successive layers, with individual thicknesses of some tens of kilometers; the layer immediately below any sedimentary layers which may be present is generally known as the "granitic" layer, and the other layers are imagined to be similar, on the average, to more "basic" rock types; (2) in mountainous regions and generally in regions of high elevation, the upper layers are thicker than in the "normal" crust, so that "abnormal" heights are supported primarily by "roots" displacing denser underlying material. The first proposition embodies the main seismological results concerning the structure of the crust. The second, based originally on the observation that mountains do not "pull their weight," gravitationally speaking, comprises also a geological interpretation of the reason for this phenomenon, in agreement with observations of folding and thrusting, and with some seismological support. It is not necessary for present purposes to specify the mechanism by which crustal thickening is brought about.

Now to these two propositions, we may add a third which rests upon much more dubious evidence. This is the proposition that very nearly all of the heat which is known to flow to the Earth's surface is produced radioactively in the "granitic" layer. The principal argument for this is that an average concentration of radioactive elements of the order of that found for the surface rocks, in particular for "granitic" rocks, to a depth of ten km or so, would suffice to supply all of the known loss of heat from the interior. This line of thought has been carried to its most extreme form, probably, by BULLARD, [see "References" at end of paper, 1939], who has used his excellent determinations of heat flow in South Africa to estimate a maximum thickness of the granitic layer. Like all such estimates, this one depends upon the basic assumption that the average amount of radioactivity for the whole "granitic" layer is equal to some value found as the mean for a number of rocks collected as granite.

I do not intend to argue with this assumption for the present but to accept it and to trace out the consequences, when it is combined, as it must be, with our two initial propositions. In brief, if all, or nearly all of the heat production is in the granitic layer, and if this layer is thickened under the mountain ranges, then the flow of heat in and near the ranges must, in time, be perceptibly greater than at sea level. Our present task is to translate this simple idea into quantitative terms so that a test may be possible.

A word on the ultimate bearing of this problem may be appropriate. To my mind, no single outstanding problem is more important for an understanding of geological processes than the problem of the distribution of temperature throughout the upper 100 km or so, as dependent upon such factors as time, sedimentary cover, and deformation; and probably no geological or geophysical problem has resisted solution more stubbornly. The principal difficulty is our ignorance of the distribution of the radioactive heat-producing elements. We have no difficulty in finding possible distributions, consistent with our meagre observational data. But none of the possible distributions really imposes itself as conclusive. The differences between the possible distributions with regard to temperatures are very great, and probably entirely different geological processes would have to be invoked for some of the more extreme types. Thus, every conceivable method of introducing further restrictions on the possible distributions requires careful study.

An obvious method of evaluating the mean radioactivity of the granitic layer is to determine the heat flow in the Pacific Region, where this layer is commonly judged to be absent. This is a most important project, but not an easy one. Measurements in drill-holes on atolls may be the most feasible approach. In the meantime, the study of heat flow differences in regions of different elevation may furnish indications of true average values which are difficult, if not impossible, to determine by any other method.

To return then to this problem, we have, first, to specify a structure for analysis in terms simple enough for quantitative treatment, but resembling a natural structure with sufficient fidelity so that ultimately a significant observational test may be made. We have next to compute the heat flow in and around this structure, taking into account the time elapsed since its formation. Finally, we have to discuss these results in terms of field observations which have been made or which may be made.

I have selected for this purpose the high Plains and Front Range of Colorado, and we may first examine briefly some well-known features. The Front Range rises rather abruptly from plains which are themselves from 5000 to over 6000 feet above sea level on the eastern flank. The western border is less clearly defined and other ranges rise at intervals over the entire thousand miles between the Front and the Pacific; we may for present purposes take the width of the range to be 120 km, which includes most of the Sawatch and Park Ranges, and the length as indefinitely great. Figure 1 shows the 10,000-foot contour in this region, and also, shaded, the areas of Pre-Cambrian exposure. Except in the Parks, the Pre-Cambrian is exposed over a considerable fraction of this area, and consists of the usual granites, schists, gneisses and undifferentiated elements. The radioactivity of a few of the granites has been studied by EVANS and GOODMAN [1941], and the average amount is somewhat higher than for the average North American granite. Gravity has been measured at a number of stations in this region. Reduced by Hayford's method, the anomalies average + 22 mg for four stations in the mountains and - 14 mg for five stations in the Plains, with a depth of compensation of 113.7 km. HEISKANEN [1939] has reduced the older measurements according to several more realistic schemes of compensation with about the same results. The outstanding fact is that the Range and Plains are very nearly in balance; the Plains seem to have a slight excess of compensation, the Range not quite enough. The results of the more recent traverse by WOOLLARD [1943] seem also to agree in general with this conclusion. We shall assume that columns of equal area are of equal weight in both regions. In Figure 2 is shown the elevation along three east-west sections, through Fort Collins, Denver, and Colorado Springs; these are nearly equally spaced from north to south, and do not pass through the highest peaks. For purposes of computation this topography is schematized as a block 120 km wide, 3 km above sea level, with plains on both sides 2 km above sea level. This is a slight exaggeration of the true elevation on the eastern side, which is nearer 1.5 km.

The epoch of mountain formation of which these Ranges are remnants is supposed to have reached its climax at the close of Cretaceous time, or roughly 50 to 70 million years ago. It seems reasonable to assume that no appreciable folding or thickening has taken place since that time, although it is known that uplift of a considerably eroded area, more or less coincident with the region under consideration, occurred in Pliocene and Pleistocene time. If we suppose that all of the thickening took place at least 50 million years ago, and ignore the effect of the more recent uplift, which would steepen the observed surface gradients slightly, we shall obtain values of heat flow which tend to be minimum values for the Ranges. (There is of course a difficult question as to just when the "roots" were formed under the Plains.)

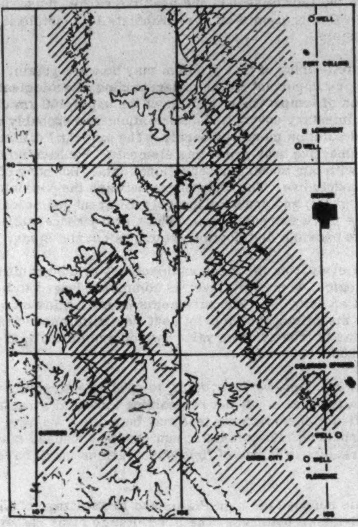


Fig. 1--Map of the Front Range in Colorado

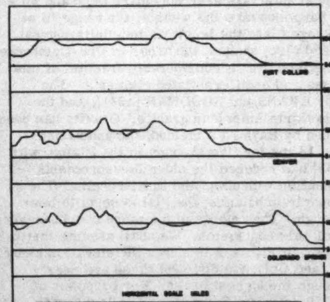


Fig. 2--East-west sections through the Front Range

We now need a definite working hypothesis for the structure below the surface. Figure 3 shows one set of assumptions for which I have carried through the calculations. For reference, we take a "normal" or sea level crust with the "granitic" layer 15 km thick, overlying an intermediate layer 20 km thick. The densities of the upper, intermediate, and lower layers are taken as 2.7, 3.0, and 3.3. Regions of higher elevation are supposed to arise from thickening of the upper two layers by equal ratios; as a result of this assumption, for every km above sea level, we thicken the upper layer by 3.3 km and the intermediate layer by 4.4 km. Sedimentary rocks of lower density may be converted into equivalent thicknesses of upper layer. In the Range, the upper layer itself is exposed at high elevations and the residue of sedimentary material in the Parks is relatively small. On the Plains to the east, the top of the Basement rocks lie somewhere near sea level covered by roughly 1.5 to 2 km of sediments. The assumed structure is essentially a regional compensation of the Airy type, and the densities are such as to require almost a minimum of roots.

We have then to consider, first, how the heat flow in the Plains differs from that of the "normal" crust, and second, how the heat flow in the Range differs from that of the Plains. In the calculations, the thermal diffusivity has been taken equal to 0.01 cm^2/sec or 32 km^2/million years, (the second set of units is more convenient for such purposes) for all of the materials. This is a good value for many rocks; the chief effect of such corrections as might be desirable from this point of view would be a slight shift of the time scale. The details of these calculations will be reported

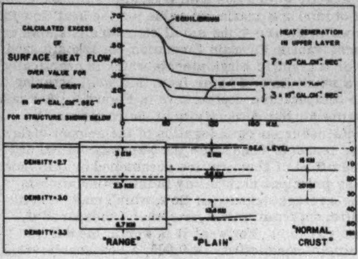


Fig. 3--Assumptions for computations

Now we assume that the Plains differ from the "normal" crust in that an extra thickness has been added to the upper layers; for the purpose of finding minimum effects, we suppose that this extra thickness was added at the base of each of the normal layers. The lateral extent of the Plains is so great and the surface slope so gentle that the problem may be treated in terms of layers of uniform thickness, and indefinite extent. For a Plain two km above sea level, we have to evaluate the effects of the following differences from the normal crust: first, there are two km extra, above sea level; second, there are 4.6 km of additional upper layer, between depths of 15 and 19.6 km replacing intermediate layer material; third, there are an extra 13.4 km of intermediate layer, between 35 and 48.4 km, replacing lower layer material. If these changes are supposed to have taken place 50 million years ago, we find that the heat flow from the uppermost two km has essentially its ultimate or equilibrium value; that from the extra 4.6 km of upper layer we are now receiving 78 per cent of the ultimate heat flow, and from the 13 km of intermediate layer, 54 per cent of the ultimate heat flow. These results are exhibited as heat flow additional to that from the "normal" crust on several assumptions as to amount of heat produced in the upper layer. In the upper curves, this is taken to be 7×10^{-13} cal/cm^3/sec, or 22 cal/cm^3/my, slightly less than the value taken by Bullard for South African granites; in the lower curves, the value is 3×10^{-13} or 9.5 cal/cm^3/my. In both cases, the heat production in the intermediate layer is taken as 1×10^{-13}, and the heat production in the lower layer is neglected. Also, in both cases, curves are given for no heat production in the upper two km; with a proper allowance for the radioactivity of the sediments we should find an intermediate curve.

We next pass to the Range. In addition to what we have already found for the Plains, we have an additional one km of upper layer at the top, and extra 2.3 km between 19.6 and 21.9 km, and an extra 6.7 km of intermediate layer between 48.4 and 55.1 km; but these extra thicknesses are not of indefinite extent; they are only 120 km wide. Their effect can be obtained in several ways; the simplest is to treat them as steady plane sources of heat of finite width, at the various levels involved. In this way, we find the curves over the region marked "Range." The deeper the source of heat, the more widely its effect is felt, but on the other hand, the smaller is its effect at the present time. The values for the close neighborhood of the junction between Range and Plains are approximate, and evidently cannot be taken too seriously, since this is the region where the general configuration of the schematic structure differs most widely from the real sloping profile. The effect of the Range upon the heat flow in the Plains is confined to a rather narrow region, not more than a few km wide. On the other hand, the heat flow in the Plains exceeds that in the "normal" crust by a measurable amount, with a still greater increment within the Range itself. If the average rate of heat production within the upper layer is as great as 7×10^{-13}, the difference between the Great Plains and the Rocky Mountains should be observable with reasonable certainty; if it should be as low as 3×10^{-13}, the difference may be concealed by errors of measurement.

Leaving the discussion of the many other conceivable cases for a more detailed report, I would now like to turn to the question of observed heat flow. We have to determine heat flow in the Earth by making two kinds of measurement, one of the temperatures at various depths in a well or mine, and another of the thermal conductivity of the rocks in which the temperatures are measured. Such determinations of heat flow are very scarce indeed; the fundamental importance of conductivity in relation to thermal gradients does not appear to have been generally realized. The best determinations of heat flow are unquestionably those of Bullard in South Africa, and of BENFIELD [1939] in Great Britain, and recently, in California [1947]; results for Persia are said to be awaiting publication, and in all likelihood should bear rather directly upon the problem we have been discussing. Temperatures have been measured in several wells east of the Front Range by VAN ORSTRAND [1937], and temperature measurements abound for Kansas and Oklahoma. In using these measurements for our purposes we are confronted with the difficulty of making convincing estimates of the conductivities of sedimentary rocks, at best loosely described in well logs. Probably the only satisfactory solution is to obtain numerous samples of rock from wells in which good temperature measurements have been made, or can be made, and to measure the conductivities in the laboratory, as has been done by Bullard and Benfield. I recently obtained temperatures to 2800 feet in a well drilled near Colorado Springs, at a surface elevation of 6200 feet and thought to penetrate the Basement rocks. The question of exactly where this well encounters the Basement is still somewhat uncertain, but for the purpose of obtaining a maximum value for the heat flow this is not too serious. The location of this well is shown in Figure 4; the small structure is known as the Red Creek anticline; the well starts in the Pennsylvanian Fountain formation, an arkosic sandstone which appears to overlie either true granite or a granitic conglomerate which is practically indistinguishable from Basement rocks. There is a small flow of water from this well, entering at about 2300 feet, judging from the evidence of the temperature-depth curve in Figure 5. A rough value for the conductivity of the rocks may be obtained from consideration of the amount of flow, the length of time since the well was drilled and the offset of temperature occasioned by this flow. The principal uncertainty in this calculation is the average quantity of flow, which may be quite different from what it was when I measured it, one gal/min. For what it is worth, the derived value of conductivity is 0.005, a reasonable value. With this value and the observed gradient of 20°C/km, the surface heat flow is 1×10^{-6} cal/cm^2/sec. If, however, we want to find a maximum value, we may take for the conductivity the value 0.007, which is unlikely to be too low for any materials encountered is this well, and we obtain 1.4×10^{-6}. This is about equal to Benfield's mean value for Great Britain, and slightly greater than his value (1.29) for the California well at an elevation of 680 feet. Van Orstrand has measured the temperature in wells near Fort Collins, Longmont, Calhan, and Florence. All of these are in the Pierre shale for most of their depth. The measurements are plotted in Figure 6. The gradient increases with depth in several of these wells, a fact which might lead one to suspect the influence of a removal of glaciation or at any rate an increase of surface temperature in recent times. I have examined the curves with this possibility in mind, but the magnitude of the change of gradient, and the fact that some of the curves, for the same general region, show very different effects, lead me to believe that the main cause of variation of gradient is probably local variation of conductivity. In any case, the gradient in the deeper portion of the wells will be very little affected by changes of surface temperature, and I have used these values, shown in Figure 6, to calculate the conductivities, taking the heat flow in all cases to be 1.4×10^{-6}, as for the Red Creek well. These are reasonable for shale, as suggested by Benfield's numerous values, but what the real values are for the Pierre shale in these localities we still do not know. I have measured a sample collected from a fresh surface cut, and obtained the value 0.002, but even in this unusually uniform formation there must be considerable differences, both laterally and vertically, as is suggested by the changes of gradient in any one of these four wells with depth. A great deal of work remains to be done in this respect. For a well near Syracuse, Kansas, BASS [1926] found a gradient of about 28°/km in a thick layer of limestone with a little shale. Here the conductivity is probably not less than 0.005, giving an estimated minimum heat flow of 1.4×10^{-6}.

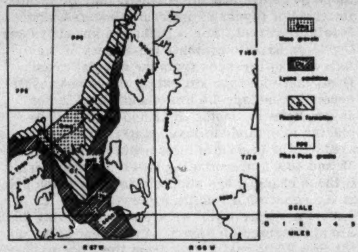


Fig. 4--Surface geology and topography over the Red Creek Anticline

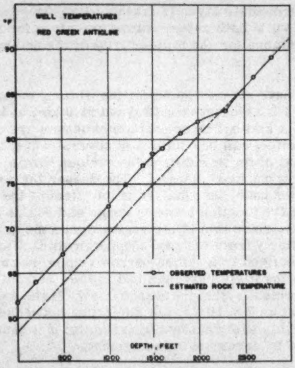
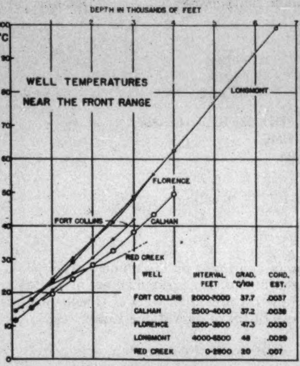


Fig. 5--Temperature-depth curve for 2800-foot well, Red Creek Anticline

Bullard's South African measurements are of particular interest for here we have heat flow determinations on a "plain" at elevations between 4000 and 5000 feet. There are really two sets of measurements here, one in the Witwatersrand region, and one in the Carnarvon region. The values of heat flow in the Witwatersrand fall between 0.95 and 1.28, with a mean value of 1.09. Here, although the surface elevation is about 1.5 km, the regions of the measurements are surfaced by great thicknesses of quartzites and dolomites, in all likelihood of very low radioactive content, which with other formations, may total over 11 km in thickness. If our picture is roughly correct, the granitic layer must be abnormally thin in this region, with the expectation of a low heat flow. Five hundred miles away, at Carnarvon, the elevation is 4060 feet, and granite and gneiss are reached at a depth of 2700 feet. Here the upper layer should be somewhat thicker than normal, and the heat flow is found to be 1.52. The difference in thickness of the granitic layer between the Rand and Carnarvon, amounting to roughly 10 km, corresponds to a difference of heat flow of about 0.4×10^{-6}, and thence to a figure for the average rate of heat production of 4×10^{-13}, rather than the 7.4×10^{-13} used by Bullard in discussing the thickness of the upper layer. A provisional value for Persia is given as 1.3×10^{-6}, without details [BULLARD, 1945].

Thus, with our present data, it is difficult to perceive any systematic difference of heat flow between regions of "normal" structure or low elevation, and regions of higher elevation, but the data include no determinations for regions above 6200 feet. I hope that it will prove possible to obtain measurements in some of the higher parts of the Rockies, and information as to opportunities for such work will be greatly appreciated. Perhaps even more favorable locations exist in some of the high South American mines.



WELL	INTERVAL FEET	GRAD. °C/KM	COND. EST.
FORT COLLINS	2000-3000	37.7	.0037
CALHAN	2500-4000	37.2	.0038
FLORENCE	2500-3800	47.3	.0030
LONGMONT	4000-6500	48	.0029
RED CREEK	0-2800	20	.007

Fig. 6--Well temperatures near the Front Range

If further work should definitely establish what is now merely an indication, namely, that the heat flow is nearly independent of elevation, then there seem to me to be two main lines of interpretation: either the average rate of heat production in the upper layer must be relatively low, or else there can be no such thickening of the upper layer under high land as is commonly supposed. These alternatives need not defy resolution, as ultimately it should be possible to determine the real profile of the upper layer in mountainous regions by seismological methods. A low rate of heat production in the upper layer means that more of the observed heat must originate below this layer than it is generally accepted at present. This in turn means higher temperatures throughout the crust. Once the average radioactivity of the uppermost layer has been determined within reasonable limits, the problem of the temperatures within the crust will be well on the way towards solution.

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Transactions, American Geophysical Union Volume 28, Number 5 October 1947

GEODETIC WORK IN MEXICO DURING THE PERIOD FROM MAY 1945 TO MARCH 1946

Manuel Medina

(Translated by Frank L. Culley and F. W. Darling)

Triangulation

During this period the observation of geodetic angles was continued on the triangulation project to which reference was made in the previous report, and in addition measurement of angles was begun on a new triangulation arc along a segment of the 101st meridian west of Greenwich between triangulation along the 20th and 26th parallels. Details of these operations follow:

(a) The triangulation along a segment of the 104th meridian, west of Greenwich, was completed with the observation of 19 stations of which some had to be repeated because allowable tolerances had been exceeded. In the development of this triangulation we encountered rugged areas, absence of communication lines and on some occasions unfavorable conditions for observing, which obligated us to accept angular closures somewhat greater than permissible, provided that the discrepancy in the base check did not exceed 1:25,000.

In the one case the triangulation which we describe briefly, in which this difficulty occurred, a preliminary computation of the linear closure was made which gave a value outside of the prescribed discrepancy. For this reason reobservations were made at some stations where the greater angular errors existed.

(b) The triangulation in the State of Guerrero is in the process of being completed inasmuch as observations were lacking on only three of the stations situated on the high peaks of the Sierra Madre Occidental.

(c) The triangulation in the neighborhood of Parícutin, Michoacán was completely finished and the ties with the topographic stations situated in the proximity of the volcano were completed by Kenneth Segerstrom of the United States Geological Survey.

After the triangulation observations had been made an invitation was received from Richard E. Fuller, President of the International Commission for the Study of Parícutin, to have determined the positions of the gravity and magnetic stations which had been established months before by Romberg and Barnes of the firm of La Coste and Romberg, Austin, Texas, and by Austin Jones of the United States Coast and Geodetic Survey.

In order to determine these positions, stadia traverse and topographic leveling were run for a distance of approximately 45 km, this survey being based upon the Segerstrom stations.

(d) The triangulation along the 26th parallel was completely finished between the arcs along the 98th and 104th meridians west of Greenwich.

(e) Reconnaissance and observations for new triangulation on a segment of the 101st meridian were begun, starting from the line Culiacan-Guante of the Rio Lerma triangulation. Observations at the present time have been completed on the following stations: Guante, Culiacán, Temascatío, Celaya, Alto del Chorro, Palo Huérfano, San Antón, and Tequisquiapan.

Reconnaissance was begun at the same time for this same arc from the line Jabali-Encantada of the triangulation along the 26th parallel southward through the State of Coahuila. Observations at present have been made on the following stations: Jabali, La Leona, Encantada, Pedregoso, Fraile, and Astillero.

Astronomic positions

In order to establish control points immediately usable in cartography, the following astronomic stations were established: San Bartolo, Q. R.; Tiringeo de la Jaqueca, Mich.; Huajinic, Nay;

Vistahermosa, Gro.; Guadalupe Ocotán, Nay.; Oxipaco, Méx.; Tuxpan, Nay.; San Javier, Mex.; Puente de Camotlán, Nay.; San Simón de Guerrero, Méx.; La Manga, Nay.; Huipililla, Gro.; San Martín, Nay.; Lagunillas, Gro.; Amatlán de Joray, Nay.; La Cucha, Mex.; Las Mojarras, Nay.; Tlapanco, Méx.; Hostotipaquillo, Jal.; Loma del Chivo, Gro.; Rancho Viejo, Gro.; and Cuahulote, Gro.

Operations at all of these stations were by expeditious astronomic methods with the object of obtaining the respective positions with a precision of ± 5″, using portable instruments such as the sextant and 10-second theodolite. The results are comparable to those obtained with the prismatic astrolabe for the determination of control points used in the restitution of trimetrogon photographs.

Gravity

Gravity determinations were renewed, a new gravity circuit having been initiated, starting from the base pillar in Tacubaya, and has been carried at present through the States of Veracruz, Tabasco, Chiapas, Yucatan, and Territory of Quintana Roo. The pendulum equipment which is used in these determinations is of the Coast and Geodetic Survey type, fitted with an invar-steel pendulum.

Precise leveling

Precise leveling has been continued in Mexico Valley in agreement with the Committee for the Study of Subsoil in Mexico City.

Likewise, leveling for the Pan-American Highway was continued to the end of the past year, extending at this time some km north of Pachuca, Hidalgo.

Photogrammetry and cartography

In the period of this report the aero-photogrammetric survey of a zone of the State of Tabasco, which embraced an area of approximately 7610 sq km, was completed. This aerial survey was contracted by this Institution with the Compañia Mexicana Aerofoto, to whom were furnished the necessary astronomical control points for the construction and fitting of its mosaic to a scale of 1:500,000. The aforementioned mosaic will be used immediately by the National Irrigation Commission for studies connected with the hydrological improvement of that State for its agricultural development.

From the geographic and cartographic viewpoint, this mosaic is not of great interest to this office, but it is going ahead with the use of the contact photographic prints to make a topographic map of the region covered.

In accordance with the established cooperation between this office and the International Committee for the Study of Parícutin Volcano, construction of a topographic map of that region was also undertaken. To this end, using the aerophotographic material obtained by the Committee in periodic flights, two maps were constructed, the first for the prevolcanic epoch and the second at a later date, in which the advance of the lava in three epochs is estimated, the last being in May, 1945.

Both maps were made on a scale of 1:20,000 with a contour interval of 20 m. The Fairchild stereo-comparagraph was used in their construction, the planimetry depending on topographic triangulation established previously on the ground. Using aerial photographs of the State of Jalisco taken by the Air Force of the United States of America and furnished to this office, and aided by geodetic and topographic control points established by the field-brigade from this Bureau, progress has been made on the construction of the topographic map of the State of Jalisco on a scale of 1:100,000 with a contour-interval of 100 m.

Details of the triangulation work and of the topographic work are available from the author through the address below.

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COAST GUARD PLANS FOR OCEANOGRPAHIC WORK

Joseph F. Farley

As the title of this report indicates, there is little to add to my report of last year concerning the Coast Guard work in oceanography. As is generally known, the work of the Coast Guard in oceanography is tied very closely to our responsibilities for International Ice Patrol. Since the suspension of that service during the war years and the cessation of the oceanographic program in connection therewith, no full-scale program has been resumed. The service is still dogged by diseases of demobilization, and it has not been possible to make oceanography an active part of the ice patrol program in 1947 as was expected. However, the ice patrol has been resumed, and was conducted in 1946, and is in progress in 1947.

Such oeanographic observations and investigations as have been possible under the circumstances have been conducted. These consisted primarily of bathythermograph observations and the construction of surface isothermal charts of the Grand Banks region every two weeks during the ice patrol season. These charts and associated iceberg drifts indicated unusual current patterns during 1946, and dynamic investigations would have been interesting and valuable. Our ships of the ice patrol and ocean weather station vessels have sent literally thousands of bathythermograph slides to Woods Hole Oceanographic Institution and Scripps Institution of Oceanography. The steadily accumulating data from this source must be adding materially to our knowledge of diurnal warming, depth of the mixed surface layer, internal waves and vertical temperature sections across major ocean currents. This program will be continued as long as the services mentioned are continued. Ships have not been available for the usual post ice season cruises to the Labrador Sea and Davis Strait during which certain oeanographic sections were periodically rerun. It is hoped that this phase will also be resumed in the future.

It is not possible at this time to evaluate the effect that the war-nurtured technological and scientific advances may have on the oceanographic studies of the Coast Guard in connection with ice patrol. Certainly procedures and techniques will be changed and results should improve. Similar advances in other aspects of ice patrol will call for a review of the need for such research. The greatest change already made is the supplementing of surface patrol by the use of land-leased, long-range aircraft for scouting the ice areas. In any case, the Coast Guard plans to inaugurate, when practicable, the following tentative and general oceanographic program: (a) Resume periodic oceanographic surveys of the Grand Banks region during the ice patrol season with completely equipped and suitably staffed vessel or vessels; (b) resume periodic post-season oceanographic and ice-survey cruises in the Labrador Sea, Baffin Bay, and Davis Strait region to rerun the old standard oceanographic sections and resurvey these important bodies of water for long-term changes as they affect ocean circulation and hence the distribution of ice in the North Atlantic Ocean; (c) participate in the development and test of a continuously-recording, temperature-depth-salinity instrument of sufficient accuracy for large-scale, surface-to-bottom, oceanic, and dynamic surveys (this is already being done);(d) continue, as in the past 30 years, to apply all new developments and techniques to the Coast Guard oceanographic program and to develop new instruments and techniques in order to increase our knowledge of the oceans and our ability to gain that knowledge.

The Coast Guard will, in addition to this basic research program, continue as in this past year to cooperate with all agencies of the Government and private institutions in programs where the peculiar facilities of the Coast Guard lend themselves to the collection of oceanographic data. I mention specifically the following: (a) Coastal current surveys and wind and sea data for the Coast and Geodetic Survey;(b) a broad cooperative program of long standing with the United States Weather Bureau, which includes among its many items, collections of sea water temperature from selected coastal stations; (c) SOFAR project and observation of swells with the Navy.

U. S. Coast Guard,
Washington 25, D. C.

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RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1946 TO APRIL 1947

H. U. Sverdrup and Staff

(Contributions from the Scripps Institution of Oceanography, New Series, No. 332)

In September 1946, Norris W. Rakestraw joined the staff of the Scripps Institution as Professor of Chemistry. He has been engaged in instruction and the planning of a research program in chemistry.

G. F. McEwen has completed the tabulation of a number of functions which repeatedly occur in a variety of oceanographic problems. He continued his work on the theory of dispersion of material in the sea from given area and volume sources, introducing different assumptions regarding initial conditions and coefficients of diffusion. Several of the theoretical results have been applied to questions as to the dispersal of the radioactive material deposited in the water after the atomic bomb explosion at Bikini.

Research work has been started on the dynamics of large horizontal eddies (axis vertical) characteristic of the ocean off southern California. Preliminary work based upon 1940 and 1941 observations indicated that after its formation such an eddy increases in area and decreases in intensity according to a solution of the hydrodynamic equations corresponding to an initial concentration of vortex motion within a circular area of more than 10 km in diameter. The solution of this problem depended upon earlier work on diffusion from a circular area, and the numerical work requires the fundamental tables already computed for the diffusion problem. Extensive supplementary tables have been computed for ready numerical application to specific problems of diffusion from a circular area and the behavior of horizontal eddies.

The major part of the research in physical oceanography and submarine geology has been carried out under Navy contracts. This work comprises analyses of bathythermograph observations, analysis of ocean currents, studies of sea and swell, and examination of beaches and submarine topography in shallow water.

Dale F. Leipper is undertaking an examination of the relation between the meteorological conditions over the ocean and the thermal structure of the surface layer, but the very frequent occurrence of internal waves of periods ranging from 10 or 15 minutes up to 24 hours makes it extremely difficult to examine changes in the heat contents of the waters. A great amount of time has therefore been spent in devising methods for eliminating the effect of internal waves.

Near the coast off La Jolla large temperature fluctuations have been found which appear to be related to intense mixing which occurs when tidal currents flow over a very irregular bottom. In summer, this mixing may bring water to the surface from such depths that locally the surface temperature may drop as much as six degrees centigrade within ten minutes. These features will be examined in detail. Leipper is also carrying out a study of methods for improving the forecasting of fog in coastal areas, making use of knowledge of sea-surface temperatures.

The analysis of ocean currents undertaken by W. W. Wood has dealt with the statistical significance of such average currents as are represented on different types of charts. An analysis is in progress of variability in currents which may be apparent only because the observations are obtained from ships which may have crossed or followed a narrow current. The observed set in 24 hours may in such cases depend very much upon the course of the ship.

In the studies of sea and swell by W. H. Munk and R. S. Arthur the concept that wind waves are impulsively generated has been a very fruitful one which has led to a better understanding of the observed characteristics of swell. The physical basis for the forecasting procedures which were developed during the war is steadily being improved and at the same time a number of conclusions have been arrived at which can be tested when suitable ovservations become available.

The theory of impulsively generated waves has also been applied successfully to tsunamis. It appears possible that records of tsunamis can give information as to the extent in space and time of the initial disturbances of the sea surface which generated the train of waves.

A. R. Champion has completed the installation at a depth of 40 feet of one recording wave meter off the Scripps Institution pier. Two other wave meters at depths of 120 and 600 feet will be installed in the near future. These wave meters were built by the Department of Mechanical Engineering at Berkeley. Work on analysers of wave records has been started in cooperation with the Woods Hole Oceanographic Institution.

F. P. Shepard has carried out systematic studies of beach profiles at a number of localities in the vicinity of La Jolla and in connection with these studies has made records of breaker characteristics and of longshore currents. Detailed examinations of rip currents have been made off La Jolla. With the aid of a diver the heads of the canyons in the La Jolla area are being examined. The Navy has placed a buoy boat at the disposal of the Institution and this is being equipped with a shallow recording sonic depth finder in order to undertake repeated surveys of the bottom topography in the La Jolla Bay. Special sand traps will be used to examine details of sand movement and compare findings with changes in the bottom topography.

The most gratifying development is the interest shown by young men in the study of oceanography. In the spring semester of 1947, 41 graduate students were registered at the Scripps Institution, including nine from other countries. Twenty-six of these students are specializing in physical oceanography or submarine geology, and most of them participate in the different research projects in progress.

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Compiled by Clyde E. Houston

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NOTES AND PERSONALIA

NOTES

Submarine gravity expedition of the U. S. S. Tusk--The U. S. S. Tusk, commanded by Guy F. Gugliatta, has returned from an expedition for the measurement of gravity at sea on the continental margin between Cape Sable and Cape Hatteras. The expedition was made possible through the cooperation of the Office of Naval Research and the Commander of Submarines, Atlantic Fleet. A portion of the scientific expense was likewise met by the Office of Naval Research which has underway an extensive program of the measurement of gravity at sea, by contract with Columbia University. The major part of the expense of the scientific work was met by a grant from the Penrose Fund of the Geological Society of America. The Committee on Geophysical and Geological Study of Continents, AGU, cooperated in planning the expedition.

The scientific party consisted of Maurice Ewing, J. L. Worzel, N. C. Steenland, and G. R. Hamilton. The basic gravity apparatus was a Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer supplied by Woods Hole Oceanographic Institution. An auxiliary slow pendulum apparatus for determining the Browne correction was lent by Professor Vening Meinesz. A gravimeter provided by Columbia University was tested as supplemental equipment.

The primary purpose of the expedition was to secure detailed information on the gravitational field of the Earth over the transition from continent to ocean, including information on isostatic compensation of major topography, and on the strength of the Earth's crust. The area selected has been examined by the seismic refraction method in recent years.

Cuban vessel for oceanographic research--The Cuban Naval Vessel Donativo is to be fitted out as a research vessel to do hydrographic, oceanographic, meteorological, and fisheries investigations around the coasts of Cuba. The Donativo was originally a yacht, built in 1932, and is a wooden, twin-screw motor vessel, 105 feet long.

New publication of the American Meteorological Society--The first number of Meteorological Monographs has just been issued by the American Meteorological Society and contains a 52-page paper by W. C. Jacobs on the subject "Wartime Developments in Applied Climatology." In announcing the series, the Society states that this is "to present valuable contributions to meteorology and related fields which might not otherwise be published because of their length."

Field Conference on Loess Deposits--A midwest Field Conference on the loess deposits of the upper Mississippi Valley assembled in the vicinity of Peoria, Illinois on June 21, 1947 and proceeded over a period of seven days through the major loess regions of Illinois, Iowa, and Nebraska, to Lincoln. Representatives from Illinois, Iowa, Nebraska, South Dakota, and Kansas, and from several Federal Bureaus, were in attendance.

Earthquakes, June to September, 1947--The United States Coast and Geodetic Survey has located provisional epicenters during this period as shown in Table 1.

Table 1--Provisional epicenters of the U. S. Coast and Geodetic Survey

Date	Time U. T.		Epicenter				Remarks
			Lat.		Long.		
1947	h	m	°		°		
June 19	7	34.6	22	N	146	E	600 miles north of Guam in Pacific
July 10	10	48.8	73	N	70	W	Baffin Bay
July 10	16	05.1	14	N	93	W	Off Guatemala in Pacific
July 12	1	58.8	45	N	149	E	Kurile Islands
July 12	12	29.6	20	S	176	W	Tonga Islands
July 13	12	57.3	19	S	179	W	East of Fiji Islands
July 23	5	13.4	17	N	68.5	W	Off southwest coast of Puerto Rico
July 23	17	33.3	54	S	30	W	South Atlantic
July 24	12	16.9	18.5	S	170	E	New Hebrides Islands in Pacific
July 25	19	09.0	21	S	67	W	Northern Argentina, depth about 400 km
July 28	3	48.7	62.5	N	151	W	Central Alaska
July 29	13	43.5	29.5	N	97	E	Border of Tibet and Burma
July 31	14	12.9	0	..	84	W	Pacific Ocean off Ecuador
Aug. 5	14	24.2	25	N	62	E	Arabian Sea south of Baluchistan
Aug. 6	5	46.9	9.5	S	72	W	Near border Brazil-Peru
Aug. 9	2	48.3	1	N	28	W	Mid-Atlantic Ocean
Aug. 10	2	46.7	41.9	N	84.5	W	Southern Michigan
Aug. 27	13	37.6	42	S	179	E	Off southeast coast of North Island, New Zealand
Aug. 28	6	50.3	49	N	155	E	Off southern Kamchatka
Aug. 28	14	29.4	52	N	159	E	Off southeast Kamchatka
Aug. 28	19	48.0	29.5	S	71	W	Near coast Central Chile
Sep. 2	14	32.3	20	S	179	W	West of Tonga Islands
Sep. 3	18	56.4	11	S	162	E	Solomon Islands
Sep. 4	0	30.2	15	S	174	W	Samoan Islands

The following shocks in Table 1 are tentatively listed as deep-focus types: July 13 (100 km), July 25 (400 km), Aug. 6 (550 km), Sep. 2 (200 km). The deepest are in South America, the others in the south Pacific.

The epicenters listed were determined by the United States Coast and Geodetic Survey cooperating with Science Service, the Jesuit Seismological Association, and a selected group of widely scattered seismograph stations. In addition, the following minor shocks were reported.

On August 24 at 9:20 U. T., a light shock was felt in eastern Puerto Rico and the Virgin Islands.

On July 1 at 4:35 U. T., St. Louis reported a moderate shock felt over a 30-mile radius from the city. A few chimneys were knocked down.

On July 14, press reports indicated considerable earthquake damage at Pasto, Colombia, near the Ecuador border. The shock was not well recorded on distant seismographs.

On August 9, Michigan, Indiana, and parts of adjoining States were shaken by a moderate earthquake at 9:45 p. m. (C. D. T.). In the central area, just north of the Indiana-Ohio border, the maximum reported intensity was V (Modified Mercalli scale of 1931). The affected area was canvassed for detailed information by the U. S. Coast and Geodetic Survey. J. T. Wilson of the University of Michigan is making a special instrumental study of this earthquake.

Swedish oceanographic expedition--The Albatross, 1052-ton Swedish auxiliary four-masted schooner, which serves as a training ship for the Broström Lines, has been chartered for an oceanographic expedition under the leadership of Hans Pettersson, and has already completed the first leg of a trip around the world. The scientific program concentrates on deep Nansen-bottle stations, and on obtaining long cores in deep water with the Pettersson vacum-sampler. Fred B. Phleger of Woods Hole Oceanographic Institution was aboard the Albatross from Martinique to Colon as an observer.

Civil Service examination for Oceanographer--The Civil Service Commission has announced an Unassembled Examination No. 67 for various grades of Oceanographer. Applications will be received until further notice. For details write to the Civil Service Commission, Washington 25, D. C.

PERSONALIA

Arthur C. Bevan, State Geologist of Virginia and Chairman of the Division of Geology and Geography of the National Research Council, has been appointed Principal Geologist in charge of the Geological Survey to succeed Ralph E. Grim who will devote more time to the Survey's program of research on clay minerals.

Kenneth E. Caster, on leave from the University of Cincinnati for the past two years to serve as Director of the Department of Geology and Paleontology of the University of São Paulo, Brazil, will terminate his work there at the end of this year. He will remain in South America until autumn of 1948 to complete geological studies supported by a fellowship of the Guggenheim Foundation. His work at the University of São Paulo is a part of the program of cultural cooperation of the State Department.

Philip Donnerstag is now engaged as a geologist by the New York State Science Service on oil and gas studies in the Alleghany oil fields.

John H. Melvin has been appointed State Geologist and Chief of the Ohio State Geological Survey. He was formerly District Geologist with the Corps of Engineers in Omaha, Nebraska.

Morrough P. O'Brien, formerly Dean of Engineering at the University of California, has accepted an appointment on the staff of the Air Reduction Company in New York to direct the engineering work.

Roger R. Revelle of the Office of Naval Research supervised the Bikini Scientific Resurvey, which was organized to study the effects of the atom bomb tests one year later. Among geophysical programs carried out at Bikini in the summer of 1947 were the drilling of a test hole in the atoll by Harry S. Ladd and Joshua I. Tracy of the U. S. Geological Survey, and a new determination of the annual reef increment by Thomas S. Austin of the Division of Oceanography, U. S. Hydrographic Office.

Lorenz G. Straub, Head of the Department of Civil Engineering at the University of Minnesota, and Director of the St. Anthony Falls Hydraulic Laboratory has been given the Navy award "for exceptional service in naval ordnance development." During the war Dr. Straub served with the Office of Scientific Research and Development in the coordination of research in the development of ordnance for undersea warfare and rockets.

Harald U. Sverdrup will resign early in 1948 as Director of Scripps Institution of Oceanography, according to an announcement from the Office of the President of the University of California. Dr. Sverdrup who became director of the Institution in 1936 upon the retirement of T. Wayland Vaughan, will return to his native Norway as Director of the National Institute of Polar Research in Oslo. This Institute was established in the early 1920's for topographic mapping and geological surveying in the Svalbard-Greenland region. It will now be expanded to include meteorological, oceanographic, and biological research in both the Artic and the Antarctic.

Sherman A. Wengerd has been appointed to an assistant professorship at the University of New Mexico and will teach sedimentation subsurface geology, petroleum geology, and geologic interpretation of aerial photographs. He was formerly with the Exploration Department of the Shell Oil Company.

L. Standish Hall, Principal Hydraulic Engineer for the East Bay Municipal Utility District, died on July 5, 1947. He was born at Corning, New York, February 1, 1892, and received his academic training at Massachusetts Institute of Technology. During his early professional career, he had a wide and varied experience. His services with the Utility District began in 1924. He was the author of numerous articles relating to hydrology and hydraulics.

Otto Lütschg, retired Chief of Hydrologic Services at the Polytechnic School in Zurich, Switerzerland, and President of the Association of Scientific Hydrology of the International Union of Geodesy and Geophysics, died suddenly of an heart ailment on shipboard on Lake Geneva, July 22, 1947. He was 71 years old.

UNION, SECTION, AND COMMITTEE ACTIVITIES

Report of Committee on Audit for Fiscal Year, July 1, 1946 to June 30, 1947

A. G. McNish (Chairman), R. H. Weightman

Your Committee on Audit has examined the books of the Union for the fiscal year ending June 30, 1947, and found them in agreement with the financial statement as prepared by the General Secretary's Office and shown below. The cash balance on hand as of June 30, 1947 was $19,793.66 from which must be deducted outstanding checks in the amount of $1,850.27 leaving a net balance of $17,943.39. This includes the balance of the Robert E. Horton Fund in the amount of $4,014.41 and the William Bowie Medal Fund in the amount of $146.10, funds which are not available for the regular operating expenses of the Union. The expeditures and receipts of the Union are carefully and accurately posted and supported by vouchers.

Your Committee again would like to commend the office of the Executive Secretary for the excellence of the state of the books which, as in the preceding year, were found to be in perfect shape.

Financial Statement, Fiscal Year, July 1, 1946 to June 30, 1947

Receipts		
Cash balance, July 1, 1946 as reported from Juen 30, 1946		$13,447.41
American Geophysical Union	$13,294.31	
William Bowie Medal Fund	153.10	
Dues, 1943-1949		14,470.89
1943	$ 3.00	
1944	12.00	
1945	57.00	
1946	1,881.70	
1947	12,466.00	
1948	46.19	
1949	5.00	
Sales of publications		4,800.68
Transactions	2,755.51	
Reprints	2,041.52	
Bibliography of Hydrology	1.15	
Exhibit maps	2.50	
Miscellaneous contributions		8.72
Grants		7,400.00
Rockefeller Foundation	7,000.00	
National Research Council	400.00	
Robert E. Horton Fund		5,000.00
✓ Total receipts ($13,447.41 + $31,680.29)		$45,127.70
Disbursements		
Transactions, 3 1/2 numbers of 1946 and 2 1/2 numbers of 1947		$ 7,475.21
Reprints		1,521.23
List of Members and Officers		565.04
General expenses, Office of the Union		12,727.98
Services	$10,208.73 ✓	
Equipment	495.83 ✓	
Stationery and miscellaneous	1,104.60 ✓	
Postage and express	918.82 ✓	
28th Annual Meeting (1947)		321.83 ✓
Regional Meetings		17.25 ✓
Sections		63.16 ✓
Geodesy	6.48	
Terrestrial Magnetism and Electricity	15.30	
Oceanography	1.00	
Hydrology	40.38	

95 8/48

Committees		$ 1,587.22 ✓
Executive	$ 55.34	
Membership	195.63	
Editorial and Publication	1,336.25	
William Bowie Medal		7.00 ✓
Travel		62.80 ✓
Robert E. Horton Fund expenditures		985.59
Investment		1,850.00
Total disbursements		$27,184.31
Balance, June 30, 1947		$17,943.39[a]

Distribution of balance

American Geophysical Union, General Fund	$13,782.88	
William Bowie Medal Fund	146.10	
Robert E. Horton Fund	4,014.41	
		$17,943.39

Bills receivable, June 30, 1947		
Publications		$ 694.47
Transactions	$ 530.32	
Reprints	164.15	
Dues		3,327.00
1946 and 1947, 124 members[b]	1,237.00	
1947, 418 members	2,090.00	
Miscellaneous		4.00
Total bills receivable		$ 4,025.47

Bills payable June 30, 1947		
Harlowe Composition Co. (Stationery and Misc.)	$ 7.60	
Chas. A. Stott and Co. (Stationery and Misc.)	3.33	
Kirby Lithographic Co. (June *Transactions*)	839.27	
Guthrie Lithographic Co. (Membership Com.)	24.50	
Chesapeake and Potomac Telephone Co. (Stationery and Misc.)	6.46	
A. B. Dick Co. (Stationery and Misc.)	9.42	
Western Snow Conference (Regional Meeting)	18.68	
Joseph R. Goberna (Overpayment)	15.33	
Elliott Addressing Machine Co. (Equipment)	73.35	
Dues paid in advance	51.19	
		$ 1,049.13

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[a] Riggs National Bank, statement of June 30, 1947 .... $19,793.66

Less checks outstanding:

No.		No.	
2212	$ 0.77	2241	$ 90.60
2227	3.36	2242	45.53
2228	2.03	2243	75.00
2229	326.63	2244	75.00
2230	20.52	2245	75.00
2231	28.22	2246	75.00
2232	16.75	2247	75.00
2234	1.50	2248	75.00
2235	9.08	2249	75.00
2236	9.85	2250	75.00
2237	5.87	2251	75.00
2239	66.10	2252	112.98
2240	81.03	2253	353.98
		2254	1.27

Total checks outstanding 1,850.27

Balance June 30, 1947, as above ... $17,943.39

[b] One member owed but $2.00 in 1946

Recapitulation

Item	Fund			
	AGU General	Bowie Medal	Robert E. Horton	Total
Cash balance	$13,782.88	$146.10	$4,014.41	$17,943.39
Investment (at cost)	1,850.00	...	.....	1,850.00
Bills receivable	4,025.47	...	.....	4,025.47
Totals	$19,658.35	$146.10	$4,014.41	$23,818.86
Bills payable	1,049.13	...	.....	1,049.13
Net balances	$18,609.22	$146.10	$4,014.41	$22,769.73

Cost of equipment owned by American Geophysical Union

One 18-inch large primer Burroughs typewriter, serial No. 60A232450	$190.80
Oen 10-inch elite Royal typewriter, serial No. KHM-2076351	100.31
Two 4-inch drawer, 5 × 8-inch steel filing cases (gift)	0.00
One Globe-Wernicke, 2-pedestal, flat-top steel desk, A. G. U. No. 1, 60 × 34 inches	49.18
Two steel posture chairs	22.00
One Triner postal scale, 4 lbs. by 1/2 oz.	16.20
One Arrow stapler	6.75
One walnut flat-top desk, A. G. U. No. 2, 34 × 66 inches, with glass top	95.43
One walnut typewriter desk, A. G. U. No. 3, 34 × 60 inches, with glass top	100.72
One walnut typewriter desk, A. G. U. No. 4, 34 × 60 inches, with glass top	89.72
One walnut chair	21.50
One costumer, walnut finish	3.50
Ten desk trays, walnut finish	14.00
One 15-inch Eastman trimmer	13.50
Twelve copies, Manual of Style, University of Chicago Press	32.50
One Klera-desk	3.70
One 11-inch elite Underwood typewriter, serial No. 11-6126347	129.43
Two Emeralite gooseneck lamps, DTM Nos. 110 and 117, price $1 each	2.00
One Hallowell 28-inch steel stool, DTM No. 70	1.00
One three-fold double burlap screen, brown, oak finish	2.00
One three-section open bookcase composed of book sections Nos. 36, 100, and 1 old section without number, and book section top No. 108	1.00
One Globe-Wernicke No. 526 TW imitation-walnut desk, 55 inches, Dept. No. 99. (recent Government sales price to DTM)	31.51
One No. 617 posture chair with olive green finish, genuine brown leather upholstery Dept. No. 254	7.00
One wood revolving chair, Dept. No. 148	0.00
Two wood typewriter chairs, revolving, Dept. Nos. 31,and 131	0.00
Two pieces Masonite each 3 feet by 4 feet 9 inches	0.00
One white table	1.00
One work table on trestles, 13 feet long	3.90
One book rack	1.00
One Elliott Addressing Machine, model 80, serial No. 102285 B, on stand	315.99
Total cost of equipment	$1,255.64

[Note: The Union has a large stock of Transactions of past years available for sale, but these are carried as without value in the inventory.]

ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, JULY 11 TO SEPTEMBER 10, 1947

Acheson, Mr. C. H., c/o Tropical Oil Co, Bogota, Colombia (bd)
Allen, Major Harry B., Army-Navy Petroleum Board, Washington 25, D. C. (abdefgh)
Anderson, Mr. Albert D., 1373 B St., S. E., Washington, D. C. (c)
Anderson, Mr. John F., 1257 E. 32nd St., Tulsa 5, Okla. (b)
Armstrong, Mr. Edward R., 6023 Drexel Road, Overbrook, Philadelphia 31, Pa. (ce)
Ashley, Mr. Burton E., 1901 Fairfax St., Denver 7, Colo. (ef)
Atherton, Mr. Tracy L., 1253 No. Cedar St., Glendale 7, Calif. (ae)
Austin, Mr. A, C., 2531 S. Cincinnati St., Tulsa 5, Okla. (b)
Aycardo, Mr. Man M., Jr., International Engr. Corp., 3-F Soriano Bldg., Manila, P. I. (abdfgh)
Baker, Mr. A. M., 1165 37th St., Sacramento, Calif. (g)
Baker, Mr. Roger C., Bureau of Research, University of Arkansas, Fayetteville, Ark. (g)
Ballard, Mr. James A., 507 Raton Ave., La Junta, Colo. (abc)
Banta, Mr. Arthur P., California Institute of Technology, Pasadena 4, Calif. (cg)
Barbour, Mr. Price C., P. O. Drawer 2100, Houston 1, Tex. (a)
Barclay, Mr. M. G., P. O. Box 495, U. S. Bureau of Reclamation, Oklahoma City, Okla. (ag)
Barger, Mr. Thomas C., Aramco, Dhahran, Saudi Arabia (abcdefgh)
Barker, Prof. James R., 480 N 4 E St., Logan, Utah (g)
Barnes, Dr. Virgil E., 207 E. 33 St., Austin 21, Tex. (aefh)
Bartram, Mr. John G., 2740 E. 22nd. St., Tulsa 5, Okla. (ace)
Baughman, Mr. John P., 698 E 7 N. St., Logan, Utah (ab)
Bendixen, Mr. Thomas W., 4510 Kennedy St., Hyattsville, Md. (cg)
Beck, Mr. Niels C., Parks College, East St. Louis, Ill. (c)
Bergquist, Dr. Stanard G., 164 Maplewood Drive, East Lansing, Mich. (efg)
Berndes, Mr. A. E., Jr., P. O. Box 2332, Houston 1, Tex. (b)
Berning, Mr. Warren W., Ballistic Research Lab., Aberdeen Proving Ground, Md. (c)
Berry, Mr. William M., Prairie Farm Rehabilitation Administration, Regina, Sask., Canada (g)
Bevan, Mr. Arthur, Northeastern Forest Expt. Sta., Bankers Securities Bldg., Philadelphia 7, Pa. (g)
Blanchard, Mr. Charles H., Arkansas Fuel Co., Shreveport, La. (abh)
Bloomer, Dr. Robert O., P. O. Box 1428, University Sta., Charlottesville, Va. (fh)
Bochenek, Miss Natalie, 756 Stocking Ave., N. W., Grand Rapids 4, Mich. (c)
Born, Mr. W. T., 2607 N. Boston Pl., Tulsa 6, Okla. (b)
Bowman, Mr. Frank O., Jr., Geology Dept., University of North Carolina, Chapel Hill, N. C. (bfh)
Bradley, Dr. W. F., State Geological Survey, Urbana, Ill. (fh)
Brodie, Mr. Hugh W., Expt. Sta. H. S. P. A., Honolulu 4, T. H. (c)
Brooks, Mr. O. D., P. O. Box 2025, Tyler, Tex. (b)
Bue, Mr. Conrad D., 408 Federal Bldg., Belena, Mont. (cg)
Buffum, Mr. C. Emery, 1527 E. 36 Place, Tulsa 5, Okla. (b)
Bulpitt, Mr. Ernest I., Bishop, Calif. (g)
Burgess, Mr. Clasen E., 3052 Atwater Ave., Los Angeles 26, Calif. (g)
Burt, Mr. Wayne V., Scripps Institution of Oceanography, La Jolla, Calif. (ce)
Burton, Mr. G. A., P. O. Box 720, Casper, Wyo. (abdh)
Bychok, Mr. Victor, P. O. Box 892, Big Lake, Tex. (bh)
Calhoun, Mr. F. F., 7015 Hillcrest, Dallas 5, Tex. (a)
Callan, Mr. Edwin J., U. S. Waterways Expt. Sta., Clinton, Miss. (bh)
Campbell, Mr. Guy, Corydon, Ind. (ag)
Capurro, Mr. Luis R. A., Scripps Institution of Oceanography, La Jolla, Calif. (e)
Carman, Dr. Katharine W., P. O. Box 301, Newburgh, Ind. (h)
Carr, Mr. G. W., 1536 Commerce Bldg., Houston 2, Tex. (b)
Carter, Lt. Harry H., Scripps Institution of Oceanography, La Jolla, Calif. (ce)
Casey, Mr. S. Russel, Jr., 2203 Dunraven Lane, Houston 6, Tex. (h)
Cathey, Mr. John A., 1400 Continental Bldg., c/o Seaboard Oil, Dallas 1, Tex. (b)
Clewell, Dr. Dayton R., 4322 Hall, Dallas 4, Tex. (bdeh)
Clifford, Mr. O. C., Jr., P. O. Box 2819, Dallas 9, Tex. (adh)
Cody, Mr. C. C., Apartado 1488, Caracas, Venezuela (bfh)
Conant, Mr. E. E., 2630 23rd St., Lubbock, Tex. (b)
Cook, Lt. Marshall M., 142 Schuyler St., Boonville, N. Y., (ae)
Cornish, Mr. Lou G., P. O. Box 555 SLI, La Fayette, La. (abef)
Cozzens, Mr. R. B., Route 2, Box 523, Fresno, Calif. (g)
Crain, Mr. Hugh F., 1127 Oxford St., Houston 8, Tex. (abdeh)

Crain, Mr. Robert A., 1711 Polk St., Wichita Falls, Tex. (bd)
Crozier, Dr. William D., Research and Development Div., New Mexico School of Mines, Station A, Albuquerque, N. Mex. (bd)
Curnutt, Mr. Forrest E., 301 North Pine St., Hammond, La. (d)
Daly, Mr. John W., P. O. Box 1557, Lubbock, Tex. (bd)
Davidson, Dr. D. M., 1701 Foshay Tower, Minneapolis 2, Minn. (d)
Davis, Comdr. William S., U. S. S. Tanner (AGS-15), Fleet P. O., New York, N. Y. (ac)
Demme, Mr. William R., P. O. Box 563, Glacier Park, Mont. (g)
Devroey, Mr. Egide-Jean, 43, Rue Jourdan, Brussels, Belgium (g)
Dobyns, Mr. D. R., P. O. Box 900, Dallas 1, Tex. (b)
Dodson, Mr. Robert K., 553 East Town St., Columbus 15, Ohio (g)
Doll, Prof. Charles G., University of Vermont, Burlington, Vt. (h)
D'Ooge, Mr. Charles L., Office of Naval Research, 1030 E. Green St., Pasadena, Calif. (c)
Doolittle, Mr. Russell C., Box 51, R. R. No. 1, Pittsburgh 21, Pa. (abdfh)
Droessler, Mr. Earl G., Office of Naval Research, Geophysics Branch, Navy Dept., Washington 25, D. C. (c)
Duffy, Col. Marcellus, Qtrs. 603 E St., Wright Field, Dayton, Ohio (bcdeg)
Dunbar, Dr. Carl O., Peabody Museum, Yale University, New Haven, Conn. (e)
Duncan, Major George E., 1705 Selby Ave., Los Angeles 24, Calif. (c)
Dunham, Mr. James W., 4564 Indiana Ave., La Canada, Calif. (e)
Eckart, Dr. Carl, P. O. Box 992, La Jolla, Calif. (de)
Edwards, Mr. George J., P. O. Box 272, Bridgewater, Va. (bd)
Eisler, Mr. Joseph D., 2515 S. Delaware Ave., Tulsa 5, Okla. (bd)
Engle, Mr. A. Wendell, 314 S. Kenosha St., Tulsa 4, Okla. (abd)
Ergin, Mr. Kazim, c/o M. T. A. Enstitusu, Ankara, Turkey (abdeh)
Ericksen, Mr. George E., Geology Dept., Indiana University, Bloomington, Ind. (f)
Etchebehere, Mr. Hector, Scripps Institution of Oceanography, La Jolla, Calif. (e)
Evett, Mr. Woodrow W., 207 Creason Bldg., Columbia 56, S. C. (g)
Fearon, Mr. R. E., 1430 S. Terrace Drive, Tulsa 4, Okla. (abd)
Fisher, Mr. Ralph O., 233 W. Monroe St., Springfield, Ill. (g)
Fletcher, Major Joseph O., c/o Meteorology Dept., University of California, Los Angeles 24, Calif. (cd)
Fobes, Mr. Charles B., 28 West St., Concord, N. H. (cg)
Franks, Mr. W. E., Apartado 1329, Caracas, Venezuela, (abdfh)
Frost, Mr. Noel, Seismograph Service Ltd., 3-A London Wall Bldgs., London EC-2, England, (b)
Frowe, Mr. Eugene, 2535 Dunstan Road, Houston 5, Tex. (ad)
Fultz, Mr. Dave, c/o McEldowney, Flossmoor, Ill. (c)
Furcron, Dr. A. S., Georgia Geological Survey, 425 State Capital, Atlanta 3, Ga. (efg)
Gamer, Mr. Robert L., U. S. Bureau of Reclamation, P. O. Box 302, Chico, Calif. (fgh)
Garber, Mr. Allen J., Jr., United Geophysical Co., 595 E. Colorado St., Pasadena 1, Calif. (b)
Gerke, Mr. William D., Route 2, Box 684, Yucaipa, Calif. (g)
Gianelli, Mr. William R., 401 Public Works Bldg., Sacramento, Calif. (g)
Gilliland, Mr. J. R., 2514 Gulf Bldg., Houston, Tex. (b)
Gomez, Mr. Amalio, 1562 34th St., Sacramento 14, Calif. (g)
Goodwin, Mr. Albert B., P. O. Box 2231, Asheville, N. C. (g)
Granberry, Mr. H. E., P. O. Box 900, Dallas 1, Tex. (ad)
Grant, Prof. Eugene L., Dept. of Civil Engineering, Stanford University, Calif. (g)
Grawe, Prof. Oliver R., Mission School of Mines, Rolla, Mo. (efg)
Greenberg, Mr. Isidore, Dept. of Physics, Sampson College, Sampson, N. Y. (aceg)
Gregersen, Mr. Albert I., Gammeltorv 6, Copenhagen, Denmark (abh)
Gregory, Mr. Carter H., Shell Oil Co., P. O. Box 193, New Orleans, La. (abh)
Grossman, Mr. Irving, University of North Dakota, Grand Forks, N. Dak. (bfh)
Guillou, Mr. John C., Civil Engr. Dept., University of Illinois, Urbana, Ill. (g)
Guseman, Mr. L. F., P. O. Box 555 SLI, Lafayette, La. (abh)
Haggerty, Mr. Patrick E., 5322 Falls Road, Dallas 5, Tex. (bd)
Hall, Dr. Harvey, 4645 36th St., South Arlington, Va. (c)
Hamil, Mr. A. B., 3200 W. Dallas St., Houston 6, Tex. (b)
Hammon, Mr. Joseph B., 2015 P St., Sacramento, Calif. (ag)
Hansen, Mr. Vaughn E., Iowa Institute of Hydraulic Research, Iowa City, Iowa (g)
Hanson, Mr. Eldon G., 142 East 4th St., North Logan, Utah (g)
Hargis, Mr. A. V., Birthright, Tex. (be)
Hargreaves, Mr. George H., 138 Tivoli Way, Sacramento 16, Calif. (g)
Harris, Mr. John, 1911 W. Alabama St., Houston 6, Tex. (ab)
Hartman, Mr. Jack T., Shell Oil Co., 4604 1/2 South Main St., Houston 4, Tex. (abdh)
Hawthorne, Mr. W. W., P. O. Box 137, Bude, Miss. (b)

Hayes, Prof. Albert O., 14 Murray Place, Princeton, N. J. (bfh)
Heinrich, Dr. E. Wm., University of Michigan, Ann Arbor, Mich. (f)
Herpers, Mr. Henry, P. O. Box 775, Short Hills, N. J. (eg)
Hoffleit, Dr. Dorrit, Ballistic Research Lab., Aberdeen Proving Ground, Md. (cd)
Hohag, Mr. Walten H., Jr., 406 E. 11th St., Casper, Wyo. (b)
Holland, Mr. A. H., Route 2, Box 562, Ventura, Calif. (g)
Homan, Mr. W. L., P. O. Box 2061, San Antonio, Tex. (ab)
Homer, Mr. Leo. K., Route,9, Box 2482, Sacramento 16, Calif. (g)
Houghton, Mr. H. M., Box 2040, Tulsa 2, Okla. (bc)
Howell, Mr. Wallace E., 34 Shepard St., Cambridge 38, Mass. (c)
Hunkapiller, Lt. Col. B. B., 839th Engineer Aviation Batallion, APO 74, San Francisco, Calif. (abcdefgh)
Hyatt, Mr. Edward, P. O. Box 1079, Sacramento 5, Calif. (abcdh)
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SPECIAL ANNOUNCEMENT

General Assembly of the International Union of Geodesy and Geophysics--Attention is again called to the General Assembly of the International Union of Geodesy and Geophysics to be held in Norway, August 19-28, 1948. Persons desiring to attend as American delegates should get in touch with the Office of the American Geophysical Union at 1530 P Street, N. W., Washington 5, D. C., with information as to those who will accompany them. Those planning to present papers should forward word of this with title and abstract of the paper to the Office of AGU or to the appropriate Section Secretary as promptly as possible.

TRANSACTIONS
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PUNCHED-CARD COMPUTATION OF ISOSTATIC AND TOPOGRAPHIC REDUCTIONS

Ivan Tolstoy

Abstract--Isostatic reductions for gravity stations can be made with the aid of punched-card methods. A discussion of the precision that is needed and of the results that can be obtained is included. The method may be applied to a large volume of data with a saving in time and cost.

Introduction--The author was asked by Maurice Ewing, to investigate the possibilities of presenting the problem of the computation of topographic and isostatic reductions for the vertical component of gravity at any station on the Earth's surface in such a manner that this could be performed automatically by a punched-card calculator. Like all punched-card computations, this is essentially a question of calculating a series of tables and presenting these in such a manner as to make them readily utilizable in punched card form. Obviously, some fixed network for subdividing the Earth's surface has to be used in order to make this possible.

Following several talks with Herbert R. J. Grosch of the Watson Scientific Computing Laboratory, Columbia University, the author has satisfied himself that Ewing's original idea, namely, to utilize the naturally provided network of meridians and parallels provides an adequate solution to this problem. This paper will discuss essentially the manner in which the quantities necessary for tabulation are to be calculated, and the degree of precision of the estimates to be made thereby, leaving a more detailed study of the tabulation of the quantities thus obtained and of several secondary corrections, that is, the Bowie reduction correction for proportionality, and other modifications, for a future publication.

Although it has been shown by Hübner that Hayford's tables contain an error of approximately two per cent on the resultant effect of topography and compensation for any one compartment, because of the neglect of convergence of the verticals bounding the compensation, we have used his tables in the several computations necessary to prove our point. Our only object here is to show the feasibility of the proposed method and to get an idea as to its accuracy.

In the actual tabulation it will be more advantageous to use the formulas and tables of Cassinis, Dore, and Ballarin in their final form, which apart from their greater mathematical accuracy, are more convenient for making estimates for various depths of compensation.

Computation of attraction of each subdivision--We assume the Earth to be spherical, and of radius $R = 6.37 \times 10^8$ cm, the gravitational constant $k = 6.673 \times 10^{-8}$, and the mean density of the Earth to be $\delta = 2.67$ gm/cm^3. Consider a subdivision ABCD, bounded by latitudes ϕ_A and ϕ_D, the longitude interval, AB, being $\Delta\lambda$, and a station S. If ABCD is at a sufficiently large distance from S, its effect upon a unit mass placed at S can be obtained by assuming proportionality between this effect and the area and average elevation of ABCD. In other words, one should be able to include it entirely within a zone formed by two concentric circles of center S, and whose difference in radii $\Delta\theta$ is such that Hayford's assumption is valid, namely, that the effect of a unit area of unit elevation on S is the same, whatever its location within the considered zone.

This assumption is actually erroneous, but is sufficiently accurate, provided $\Delta\theta$ is not too large. The radii of Hayford's original template were so chosen as to reduce this error to a minimum. According to his estimate, this is not more than 0.2 mg, and only reaches that value in accidental cases, because of rapid local variations of topography within a compartment.

Consider therefore, a subdivision ABCD (see Fig. 1) with station S in the AC azimuth. Let θ_1 be the radius of a circle of center S, passing through A, measured in degrees of a great circle; θ_2 the radius of the circle of center S passing through C. The area of any subdivision ABCD is

$$S_{ABCD} = (2\pi Rh/360)\Delta\lambda = (2\pi R^2/360)(\sin \phi_A - \sin \phi_B)\Delta\lambda \qquad (1)$$

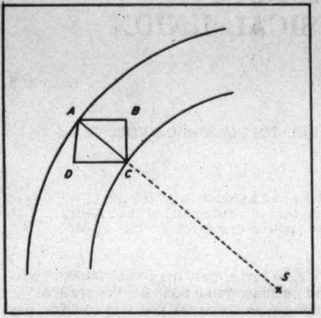

Fig. 1--Elements of a subdivision

The area of the annular zone is

$$S_{zone} = 2\pi R^2(\cos\,\theta_2 - \cos\,\theta_1) \ldots\ldots \quad (2)$$

If F be the attraction of this whole zone, supposed of unit average elevation, the effect of our subdivision, f, is

$$f = F[(\sin\,\phi_A - \sin\,\phi_B)/360(\cos\,\theta_2 - \cos\,\theta_1)]\Delta\lambda \quad (3)$$

F can be estimated by subdividing the zone into concentric subzones, of smaller $\Delta\theta$ which are summed up from θ_1 to θ_2. The effect of each one of these being given by

$$\Delta F = k\delta H 2\pi R^2(\cos\,\eta_2 - \cos\,\eta_1)[E_R] \ldots \quad (4)$$

where η_1 and η_2 are the inner and outer radii of the subzone, and E_R is the average value between η_1 and η_2 of the resultant for topography plus compensation of

$$E = \sin\left\{\theta/2 \pm \sin^{-1}[h\cos(\theta/2)/\sqrt{D^2 + h^2 + 2D_1h\sin\,\theta/2}]/(D_1{}^2 + h^2 + 2D_1h\sin\,\theta/2\right\} \,. \quad (5)$$

The values of E_R can be obtained from tables calculated by HAYFORD [see "References" at end of paper, 1912]. We note already that, as far as subdivisions ABCD of $\Delta\phi = 1$ and $\Delta\lambda = 1°$ at the Equator, the method will certainly fail for distances SC which are less than 4° or so by any appreciable amount, since zone 13 is too narrow to contain ABCD, and zone 12 is only just wide enough.

Consider such a subdivision of 1000 feet in elevation in the orientation of Fig. 1. SC is equal to 4°. We have AC = 1°24′51″. Therefore we have to apply the preceding method of quadrature to a zone of $\theta_2 = 4°$, and $\theta_1 = 5°24'51''$. Using Equations (3) and (4), we obtain the values shown in Table 1 if d_c = distance of center of ABCD from S. These 1 × 1 divisions will be used in a region corresponding approximately to zones 12, 11, and 10. Since the effect of these three zones is rarely more than 10 mg, and always less that 15 mg, we see that to be sure of a 0.1 mg accuracy, three figures are amply sufficient for all cases, and usually two will be enough. Note also that $f_1, f_2, \ldots f_5$ are calculated for distances of center from stations at intervals 5′18″, 5′18″, 10′37″, and 21′12″ respectively. Since shifts of one or two seconds have no effect upon the third significant figure, we can consider these as being intervals of 1 ×5′18″, 2 × 5′18″, and 4 × 5′18″. Then interpolating we find for f_2, $(f_1 + f_3)/2 = 253$; for f_3, $(f_4 + f_1)/2 = 240$ (21′12″ interpolation); and for f_4, $(176 + 266)/2 = 422/2 = 221$. This is not valid. We see therefore that for division of 1 × 1, the zones would have to be calculated at intervals of 20′, and for all intermediate distances their effects could be obtained by interpolation, which will save us a considerable amount of computation.

Table 1--Values of θ, f, and dc for 1 × 1 division

θ_1 to θ_2						f	dc		
°	′	″	°	′	″	10^{-7} gal	°	′	″
4	00	00	5	24	51	$f_1 = 266$	4	42	25
4	05	18	5	30	09	$f_2 = 253$	4	47	43
4	10	36	5	35	27	$f_3 = 240$	4	53	01
4	20	13	5	46	04	$f_4 = 215$	5	03	37
4	42	25	6	07	16	$f_5 = 176$	5	24	50

This would mean, from 4° to 11°, calculation of 21 zones for about 40 sizes of 1 × 1 subdivisions (other sizes can be interpolated), or less than 1000 computations.

For 2 × 2 divisions, we obtain the values shown in Table 2. Two significant figures and obviously sufficient, showing the possibility of interpolations at least for intervals of 1°, and making only nine computations for each size of 2 × 2 divisions, or about 400 computations. For 4 × 4 divisions, we could use interpolations for 2° intervals at least between successive zone estimates, and so on.

However, a slight modification to these estimates has to be introduced. If Hayford's assumption were correct, the attraction of a division ABCD would be the same whatever its orientation within a given zone. As it is, this approximation is not quite accurate enough for our case, since it will affect at least one significant figure for 1 × 1 subdivisions.

Table 2--Values of θ, f, first differences, and dc for 2 × 2 divisions

θ_1 to θ_2		f	First differences	d_c
° ′	° ′ ″	10^{-7} gal	°	° ′ ″
11	13 49 42	60	2	12 24 51
11 10	13 59 42	58	2	12 34 51
11 20	14 09 42	56	2	12 44 51
11 30	14 19 42	54	2	12 54 51
11 40	14 29 42	52	2	13 04 51
11 50	14 39 42	50	..	13 14 51

As we desire to tabulate the effect of a division of given size as a function of the distance of its center from station, let us estimate the differences in attraction between two subdivisions at an equal distance from S, but at different orientations, as shown in Figure 2. Supposing $SD = \theta_2 = 4°$, $SB = \theta_1 = 5°24'42''$ (the distance BD for a 1 × 1 division between latitudes 4° and 5° is 1°24′42″), then the radii of the zone including A′B′C′D′ exactly would be $SB' = \theta_1{}^1 = 5°15'24''$ and $\theta_2{}^1 = 4°12'25''$ (circle tangent to C′D′). (These figures were estimated rapidly by means of hydrographic tables, which are sufficiently accurate for our purposes, since the error is not more than ± 3″.)

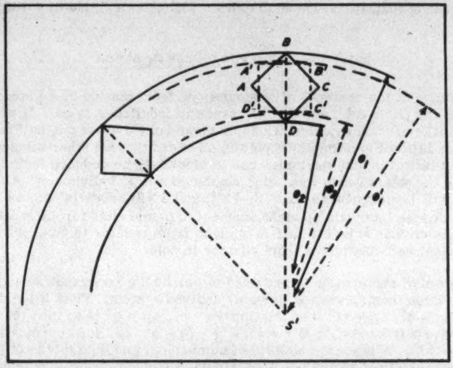

Fig. 2--Elements for modification of estimate

Using Equations (3) and (4), we obtain: f = 2656; and f′ = 2594. We see there is a difference of about 1/50 between the two estimates. However, this source of possible error can be greatly diminished by taking for both ABCD and A′B′C′D′ the average (f + f′)/2, and applying this estimate to all subdivisions of this size whose centers are at the same distance OS. The error in one subdivision is then, for the smallest distances, of ± 1/100 at the most. That the accuracy of this estimate is sufficient can be shown by noting that: (1) There are eight possible positions for which this error is zero, or practically so. (2) These errors being plus and minus, will tend to cancel out and give a much smaller total relative error. (3) This is a maximum estimate since the error is smaller for more distant subdivisions. (4) The sum total of the effects of all 1 × 1 subdivisions will always be less than 15 mg.

We see that the precision will certainly be better than 0.05 mg.

It is easy to make a similar estimate for a subdivision that is twice as high as it is long, that is, a 1 × 1 subdivision between latitudes 59° and 60°, for example, for which $\Delta\phi = 2\Delta\lambda$. In that case, for the same distance of S from center, with the two orientations as indicated on Figure 3, we have f = 1489, f′ = 1452, and the difference of 0.024.

By taking the average 1470, the error will be but slightly larger than in the preceding case... about 1/70, and in view of the already mentioned considerations, we can still depend upon having a total accuracy of better than 0.1 mg.

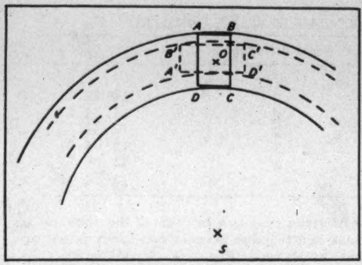

Fig. 3--Orientation of subdivision

It is easily seen that for zones exterior to 20°, divisions of $\Delta\phi = 4°$, and $\Delta\lambda = 4°$ could be used, and also for what would be about the equivalent of the Hayford zones, 5-4-3-2-1, divisions of $\Delta\phi = 8$, and $\Delta\lambda = 8$. This can be seen if one notices that if $\Delta\theta$ for a Hayford zone is less than the great circle distance between two opposite summits of a subdivision, this subdivision is too large to be utilized at that distance.

This system of using larger subdivisions for greater distances from stations, apart from reducing the number of computations to be made by means of Equations (3) and (4), or similar ones, and the subsequent machine work too, will enable us to start out by computing the average topography for large divisions and work directly with these, while the smaller subdivisions are in the process of being completed.

The preceding calculated effects would then be tabulated as a function of distance of center from station, as already indicated. These distances will be calculated by means of the haversine formula

$$\text{hav}D = \text{hav}\Delta\phi + \cos\phi_S \cos\phi_C \,\text{hav}\Delta\lambda \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where D is the distance of the center O of a subdivision from station S, ϕ_S, and ϕ_C; the difference of the latitudes of S and C_1 is $\Delta\phi$; and the difference in longitudes is $\Delta\lambda$. If we have performed once and for all, all the necessary calculations by means of (6) along one half meridian, for the 90 integer numbered latitude and longitude points, one sees that all other distances for all points of integer numbered latitudes and longitudes can immediately be deduced from the available computations, providing the whole Earth was being computed in 1 × 1 divisions. As it is, since for distant regions we will be using larger (8 × 8, 4 ×4, and 2 ×2) subdivisions, we will have to calculate (6) for eight degree intervals up eight adjacent half-meridians from equator to pole, for four degree intervals up four adjacent half-meridians from equator to pole, for two degree intervals up two adjacent half-meridians from equator to pole.

An adequate system of numeration is provided either by the geographical coordinates of the center of the subdivision themselves, or by some derived system. Thus if the distance of subdivision of center $\phi_0 = n°$, $\lambda_0 = m°$ from station $\phi_S = p°$, $\lambda_S = q°$ is a, then the subdivision whose center is at a distance a from station $\phi'_S = p°$, $\lambda'_S = (q + k)°$ has for coordinates of its center $\phi'_0 = n°$, $\lambda'_0 = (m + k)°$. With such a system of numbering, and with tables of f as a function of distance, we see that the effect of any one subdivision of unit elevation is completely determined without any ambiguity for all stations of integer-numbered coordinates.

The remaining points, the geographical coordinates of which are not integers, can be obtained by interpolation.

That this interpolation does not introduce errors of more than 0.1 mg can be seen by the following approximate reasoning: If we take two stations, S_1 and S_2 that are 1° of a great circle apart, we must estimate the area in common between their various Hayford zones. If we assume the most unfavorable conditions for interpolation, that is, brusque variations of topography within a given zone from its first position (concentric to station 1) to the second (concentric to station 2) and if then we can show that any serious error for interpolated values is highly improbable, then our point will be proved. If we assume such conditions to exist for zone 12, then the error on outer zones is bound to be less, and interpolation for all outer zones is justifiable.

The problem of calculating the area in common between two circles drawn on a sphere is more easily treated approximately in a plane without great loss of accuracy for circles of radii 4°19′ and 5°46′, since all we need is an approximate idea as to ratio of area left in common to the total area of the zone (see Fig. 4).

The estimation of the area in common between two circular annuli of equal radii 4°19′ and 5°46′ of a great circle on the surface of the Earth, and a distance of 1° between their centers can be estimated in plane by means of the formula

$$\Sigma = (\pi/90)\left[R_1^2 \cos^{-1}(d/R_1) + R_2^2 \cos^{-1}(d/R_2)\right] - 2\pi R_2^2 - d\left(\sqrt{R_1^2 - d^2} + \sqrt{R_2^2 - d^2}\right) \quad . (7)$$

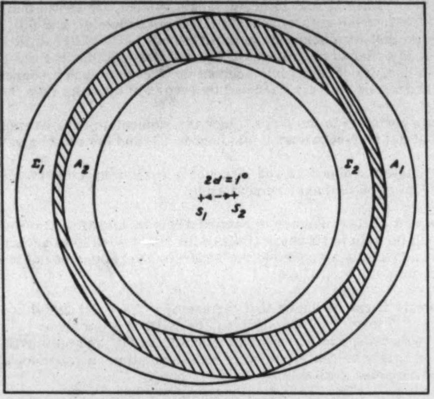

Fig. 4--Area in common between two Hayford zones

where $R_1 = 5°46'$, $R_2 = 4°19'$, and $2d = 1°$. From which it can be shown that $\Sigma = 0.55$ approximately of the total area of zone 12. If zone 12 is displaced from position 1 of center S_1 to position 2 of center S_2, with $S_1S_2 = 1°$, we see, on Figure 4 that Σ_1 and Σ_2 are the areas on the map that are subtracted, and replaced by areas A_1 and A_2. By simple geometric considerations, we can estimate $A_2 = 0.16$ of area of zone, $\Sigma_1 = 0.29$ of area. We can then assume the following, admittedly exaggerated distribution of topography: Average elevation of Σ_1, + 5000 ft; A_2, + 2000 ft; and Σ_2, 0 ft; and an average depth of A_1, $- 2 \times 271$ fathoms. The area in common (shaded on Figure 3), equivalent to 5.5 compartments of zone 12, having an average elevation of 3000 ft, so that the effects of zone 12 are, for stations S_1 and S_2: (S1) $\Sigma_1 + \Sigma_2 + \Sigma = 3.13$ mg and (S_2) $A_2 + A_1 + \Sigma = 1.68$ mg, or a difference of 1.4 mg. Actually, taking into account the narrowness of areas Σ_1, Σ_2, A_1, A_2, and their long, crescent-like shape, it is hard to imagine such brusque variations, or their equivalent, occurring in this shift, and to see how anything but a regular increase or decrease of the total effect of zone 12 can occur in the shift from S_1 to S_2, so that even in the most unfavorable cases, the accuracy of interpolation will be of the order of 0.1 mg. Actually, as soon as 1 × 1 divisions have been estimated for the whole Earth, it will be a relatively minor job to subdivide all areas of rugged topography into 1/2 × 1/2 divisions, which will leave us with the alternative of either increasing still further the accuracy of interpolated stations, which hardly seems necessary, or of bringing in the limits of the machine computations still closer to our station.

Errors caused by topographic variations within one subdivision--These errors are caused by the same results as those that arise from differences of orientation of subdivisions within a zone, by means of which their effects are being computed; namely, the approximate nature of the assumption made by Hayford. This source of error is the main cause imposing a limit upon the minimum distance at which a subdivision of given size can be treated as a unit.

Thus, if we had a 1 × 1 division, the average topography of which was zero, but with a sharp contrast between two halves, such as would exist if one part were mountainous, separated by an abrupt shoreline from a fairly deep sea fraction, it is readily seen that the half nearest to the station will have the largest effect, and the resultant effect will not be zero.

Consider a subdivision 1 × 1 of the size of those that are near the Equator. Suppose one half has an average elevation of + 5000 feet, the other half being at - 5 × 271 fathoms. This is about as drastic a topographic contrast one could expect to occur over so small an area. We can get an idea of the order of magnitude of this source of error by considering it as being placed exactly on the circle separating two of Hayford's zones in such a manner that the two natural regions...sea and land...were in different zones.

Supposing these to be zones 12 and 13 of Hayford's system, (3) shows that the two parts are respectively equal to 0.011 of the area of zone 12 (10 compartments), and 0.017 of the area of zone 13 (16 compartments) so that the difference in their effects is $3 \times 0.017 \times 16 - 3 \times 0.011 \times 10 = 0.49$ (tenths mg), that is, of an order of magnitude sufficiently large to bar the use of subdivisions this size so close to the station, if one takes into account the fact that such a source of error might occur several times and not be entirely canceled by errors of opposite sign that might occur.

Actually, the above estimate is too large, since the concentric zone estimate gives us too large a value for the effect of the half-subdivision inside zone 13, and too small a value for the other half.

If we make an estimate for zones 11 and 12 under a similar hypothesis, the maximum error is of the order of 1/50 mg, and is therefore negligible.

Actually, as soon as a certain number of computations by means of Cassinis' formulas have been performed, we will be able to fix these limits with slight additional accuracy, by computing in the manner outlined as exactly as possible the separate attractions of the two parts of a subdivision for several distances.

By a similar estimate it can be shown that the use of $1/2 \times 1/2$ subdivisions would bring our limits in another degree. Two × 2 subdivisions can be utilized from about 11° outwards, 4 × 4 subdivisions from 20° outwards, and 8 × 8 subdivisions from 60° and outwards. These limits are approximate and will certainly be subject to quite some variations as soon as a large number of accurate computations becomes available.

The reason for our choice of divisions whose areas are all four times that of the preceding smaller size, is that it is preferable that the lengths and breadths of one subdivision should all be exact multiples of any of the smaller subdivisions, or submultiples of any of the larger ones, to avoid the occurrence of misfits in our computations, which would unnecessarily complicate our task.

Note that eight is not a submultiple of 180, so that we will have to use 8 × 8 subdivisions up to within 2° of latitude of the poles, and consider the polar regions for any computation where these are outside the regions where 2 × 2 subdivisions are necessary, as subdivisions of 4° breadth having the shape of spherical caps to be included in the computations for either of the outer two lattices.

Evidently the divisions used near the polar regions can be lumped without any loss of accuracy.

Our so-called 1 × 1 divisions would then actually become divisions of $\Delta\phi = 1$, and $\Delta\lambda = 2$ above latitude 60°, thus having almost the same size as a 1 × 1 division at Equator. The 2 × 2 ones would actually have: $\Delta\phi = 2$, $\Delta\lambda = 4$, and so on.

To facilitate the subsequent work of hand computation for inner zones, for which some kind of a template has to be used, it seems more rational to establish a general rule of rejecting an integral number of subdivisions from the mechanical computation. Preferably we could use some regular pattern, such as all subdivisions contained within a larger 4 × 4 subdivision for stations of integer-numbered coordinates, and drawing out a certain number of square templates, the usual circular zones being drawn inside them, with the feature that the corners would contain fractions of zone 12, and also that zone 13 would not be entirely included in the case where we would have used 1 × 1 subdivisions (see Fig. 5).

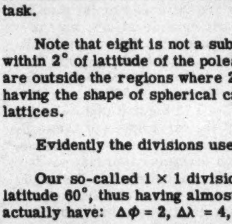

Fig. 5--Zones in a 1 × 1 subdivision

These templates will be drawn for a series of different station latitudes. The necessary corrections for the zones that are not completely present are perfectly straightforward, and can be computed once and for all for the various templates. These templates could be used also for interpolated stations.

Varying the depths and modes of compensation--We would perform all necessary computations first for one given depth of compensation. Then, proceeding along similar lines, a series of factors can be calculated which, if multiplied by the effect corresponding to the depth of compensation adopted in the first series of calculations, would give the effect of any subdivision for some other assumed depth of compensation. HEISKANEN [1931, 1938] has published a table giving such a series of factors for various assumptions as to the depth of compensation, which when multiplied by the attraction of a zone computed under the 113.7 km depth hypothesis would give the effect for depths of 40, 60, 80, 100, 120, 140, 160, and 200 km. A glance at these depths shows that the variation of these factors with distance is very slow, so that the necessary number of computations would be small. For computing the effect of the Airy-Heiskanen type of compensation, the depth of compensation for a given thickness of the crust is immediately deducible from the elevation of our subdivision, and will just involve multiplication by one of the preceding factors.

Once the first large number of computations for one given depth of compensation has been performed, and all the topography has been estimated, it will be a comparatively minor task to introduce all other depths and modes of compensation. The same is true for the correction for proportionality for subdivisions that are fairly close to a station, since in Hayford zones 10, 11, 12, and 13 in regions of rugged topography this factor cannot be neglected without introducing errors of several tenths of a mg, and is also true for the correction for elevation of station.

This can be dealt with by computing the correction for various elevations for a relatively small number of distances, and interpolating for all other distances. No difficulties should be encountered in dealing with corrections for the secondary effect of undulations of the isostatic geoid.

There is naturally, no rigid theoretical limit for the minimum distance from the station to which this method of computing reductions will apply, providing the size of the subdivisions is small enough. For example, if it were desired to apply such methods to a fairly dense network of stations covering a relatively small area, say of a few hundred square miles, the use of squares of approximatively 1 × 1 mi in the regions in the immediate vicinity of the station would enable us to reduce all of the numbered zones and lettered zones up to G inclusive, thus leaving only zones A, B, C, D, E, and F to the hand computer.

The author desires to stress once more that this paper is merely to be considered as a preliminary investigation, the only intention of which is to show the feasibility of applying punched card methods to this problem. A more comprehensive study will be made in at least one more publication, which will deal with somewhat more detail with the numerical methods involved, and give a description of the best suitable methods of tabulation, and of the machine techniques that should be used.

Advantages of this method--HEISKANEN and NUOTIO, [1938]; and HEISKANEN and NISKANIN, [1941], published world maps and tables giving the effect of zones 1 to 10. Maps and tables for zones 11, 12, and 13 were expected to follow. Though this tremendous work has for most cases considerably simplified the reductions for outer zones, the method we propose has several undeniable advantages over these world maps.

(1) It will be much more accurate. Errors due to topographic estimates will be lessened since, once the large task of estimating 1 × 1 divisions will have been accomplished, the error made on each such small subdivision will be less than that committed in the estimates made over the larger areas corresponding to separate compartments, more particularly in the case of the nearest subdivisions. The difficulties due to distortion on the zones distant from the station and in polar regions will no longer occur.

The accuracy of Heiskanen's world maps, though of the order of 0.1 mg for most estimated points, is much less for all interpolated ones. As the estimated values are spaced in 10° intervals of longitude and latitude, we see that the interpolation errors will be large. For regions of fairly abrupt topography these may exceed 1 mg. The punched-card estimates, providing the topography of closer regions is known within reasonable limits of accuracy (within a few hundred feet), should be correct by better than 0.1 mg.

(2) It will be adaptable to any new topographic discoveries which should be numerous in coming years, in particular as far as submarine topography is concerned. We would just have to replace a series of cards by another, suitably corrected.

(3) It would obviously be time-saving and labor-saving. Though it might take several hours to obtain one station separately, a large number of answers will be available after a few hours since the calculator is capable of running a large amount of computations simultaneously. This method might even prove as rapid as reading off answers from Heiskanen's map.

It is estimated that the preliminary computations of tables which can be accomplished entirely by relay-calculators and electronic calculators, should not take more than a few month's work at the most. The most cumbersome part of the task is therefore the actual map reading and corresponding tabulation, which it might take more than a year to perform.

(4) It would not take more than a few weeks work to perform all computations by means of 1 × 1 divisions for the whole North American continent, which would seem to warrant the publications of tables for all stations of integral-numbered coordinates which could be corrected every few years, or revised whenever topographic discoveries of sufficient magnitude would be made. These would barely have any effect unless situated closer than 30 great circle degrees from a station, since their order of magnitude would be such as to have effects of no more than a few hundredths of a mg at greater distances.

Summary--The main points of this paper may be summarized as follows:

(1) An example of the computation of effect of a 1 × 1 subdivision has been given, which was performed by means of Hayford's quadrature method.

(2) These should be tabulated as a function of distance of center of subdivision from station.

(3) With the system of numeration used, these distances can be tabulated for any position on the Earth's surface, by means of a comparatively small number of calculations by means of Equation (6).

(4) The largest work would consist in the preliminary map reading, it being possible to perform all other preliminary tabulations by means of mechanical calculators.

(5) The introduction of various corrections and of various assumptions as to compensation should not introduce any complications.

(6) The greater accuracy, speed, and adaptability of these computations have been mentioned.

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SURVEY-NET ADJUSTMENT BY ELECTRICAL ANALOGUE

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Abstract--This paper describes how the equivalent of a least-squares adjustment of a level or traverse net may be obtained by electrical measurements in an analogous electrical net. The lengths of the survey lines are replaced by proportional electrical resistances; the survey closures are replaced by proportional small dc voltages; the adjustment corrections are read as electrical potentials at the various junction points. The resistances, power units, and junction jacks are mounted on a panel, and are interconnected by jumpers. The closure and correction voltages are read with a special type feed-back voltmeter.

Introduction

Because of the accidental errors inherent in any kind of observed data, complete harmony in results derived therefrom can be attained only through some form of adjustment. For level and traverse survey nets this adjustment usually takes one of the several forms of least squares or a modification of one. Mathematical adjustments have been described in numerous textbooks, periodicals, and government publications [see "References" at end of paper; AVERS, 1939; BIRDSEYE, 1928; BREED and HOSMER, 1938; DELL, 1936; INGRAM, 1911; and NORRIS and SPEERT, 1940].

In this paper a method will be presented for accomplishing the same end without resort to digital computations. An electrical network will be set up exactly analogous to the survey net to be adjusted, and the desired adjustment corrections will be determined by electrical measurement. This method was developed in 1947 in the Topographic Branch of the United States Geological Survey. After a working model had demonstrated its merits in test adjustments, the writer's attention was called to a description by COWLES [1938] of an almost identical method of adjusting geophysical traverse nets. The two methods differ principally in their approach to the problem through two different forms of the least-squares analysis.

Since developmental work on the final design is still in progress, this paper should be considered essentially an interim report.

Theory

This method will be justified by first developing one of the basic relations of a least-squares adjustment; then the survey quantities will be replaced by analogous electrical quantities and it will be shown that the new relationship satisfies the appropriate laws of the transmission of electrical energy; finally, it will be shown that the distribution of current in the electrical net is identical with the distribution of error in the survey net according to the theory of least squares.

For simplicity of presentation, the discussion will be based on a network of levels, having only one type of error to be adjusted, namely, elevations. The same considerations will apply equally well to a traverse net if the latitude and longitude closures are treated separately.

Least-squares adjustment--Assume a portion of a level net, consisting of (a) one junction of three or more level lines, (b) the lines leading into the junction, and (c) the junctions or fixed bench marks at the farther end of each line. Such a portion of a net is illustrated in Figure 1, in which A is a junction the elevation of which is to be adjusted, and B, C, and D are either similar junctions, or bench marks of previously fixed elevations which are not to be disturbed by the adjustment, or a combination of these two classes. Represent the lengths of AB, AC, and AD by r_{ab}, r_{ac}, and r_{ad}, respectively.

Let a, b, c, and d be assumed elevations of A, B, C, and D, respectively. In the case of a fixed bench mark, the assumed elevation should agree with the fixed value.

Let $a + e_a$, $b + e_b$, $c + e_c$, and $d + e_d$ be the adjusted or most probable values of the respective elevations. The e-vales are the quantities to be determined by the adjustment; at the fixed bench marks they should be zero.

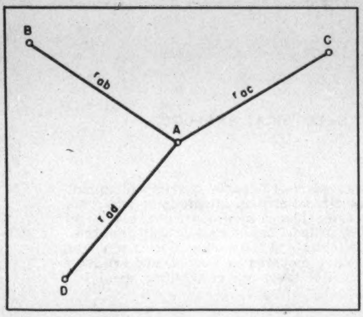

Fig. 1--Least-squares adjustment

Let $a + v_{ba}$ be the observed elevation of A on line BA, $b + v_{ab}$ the observed elevation of B on line AB. Let $a + v_{ca}$, $c + v_{ac}$, $a + v_{da}$, $d + v_{ad}$ be corresponding values on the other lines. The v-values are called closures. At the starting end of each line, the v-value will probably be zero; at any junction where the assumed elevation is taken as that observed on one of the lines into it, the appropriate v-value will likewise be zero.

Let i_{ab}, i_{ac}, and i_{ad} be the measurement error per unit length in the respective lines, or the total error in the line divided by its length. Then r_{ab} times i_{ab} (represented by ri_{ab}) is the total error in the measurement of the difference of elevation between the ends of AB, or the adjusted difference of elevation minus the observed difference of elevation. Thus,

$$\begin{aligned} ri_{ab} &= [(a + e_a) - (b + e_b)] - [(a + v_{ba}) - (b + v_{ab})] \\ &= a + e_a - b - e_b - a - v_{ba} + b + v_{ab} \\ &= e_a - e_b - v_{ba} + v_{ab} \quad \ldots\ldots\ldots\ldots (1a) \end{aligned}$$

Similarly

$$ri_{ac} = e_a - e_c - v_{ca} + v_{ac} \quad \ldots\ldots\ldots\ldots (1b)$$

and

$$ri_{ad} = e_a - e_d - v_{da} + v_{ad} \quad \ldots\ldots\ldots\ldots (1c)$$

In the ri-expressions, the v-values will be known from the observed data, and the e-values are to be determined by the adjustment.

If all lines in the net were of the same length, and the measurements of equal quality, all the errors would be given equal weight in the adjustment. However, according to the accepted theories of the distribution of errors, the strength of a survey line is inversely proportional to its length. Each line will therefore be assigned a weight $p = 1/r$. Then the most probable values of the e-quantities will be such as to make the weighted sum of the squares of all the ri-quantities in the network a minimum. Thus,

$$\Sigma[(ri)^2/r] = (ri_{ab})^2/r_{ab} + (ri_{ac})^2/r_{ac} + (ri_{ad})^2/r_{ad} + \ldots + (ri_{nm})^2/r_{nm} = \text{a minimum} \quad (2a)$$

To make $\Sigma[(ri)^2/r]$ a minimum, it should be differentiated with respect to each of the unknowns (the e-quantities), and each of the partial derivatives should be equated to zero. If e_a is considered as a typical unknown, it will be recognized that this unknown will appear only in those ri-expressions that apply to the lines entering junction A, and the effect of any other ri-terms on the value of $\partial\Sigma[(ri)^2/r]/\partial e_a$ will be nil. Therefore, the portion of a net shown in Figure 1 may be considered typical of a larger, more complex net insofar as the evaluation of $\partial\Sigma[(ri)^2/r]/\partial e_a = 0$ is concerned. Thus,

$$\begin{aligned} \Sigma[(ri)^2/r &= (e_a - e_b - v_{ba} + v_{ab})^2/r_{ab} + (e_a - e_c - v_{ca} + v_{ac})^2/r_{ac} \\ &\quad + (e_a - e_d - v_{da} + v_{ad})^2/r_{ad} + \ldots + (e_n - e_m - v_{mn} + v_{nm})^2/r_{nm} \quad \ldots (2b) \end{aligned}$$

$$\begin{aligned} \partial\Sigma[(ri)^2/r]/\partial e_a &= 2(e_a - e_b - v_{ba} + v_{ab})/r_{ab} + 2(e_a - e_c - v_{ca} + v_{ac})/r_{ac} \\ &\quad + 2(e_a - e_d - v_{da} + v_{ad})/r_{ad} = 0 \quad \ldots\ldots\ldots\ldots (3a) \end{aligned}$$

or

$$(e_a - e_b - v_{ba} + v_{ab})/r_{ab} + (e_a - e_c - v_{ca} + v_{ac})/r_{ac} + (e_a - e_d - v_{da} + v_{ad})/r_{ad} = 0 \quad . (3b)$$

Equation (3b) is the basic adjustment equation of a survey net. It contains as known quantities, the v-terms and the r-terms, and as unknown quantities, the e-terms. If similar equations be determined for each of the junctions in the net, there will be as many equations as there are unknown e-terms, and a unique rigorous solution of the simultaneous equations is feasible.

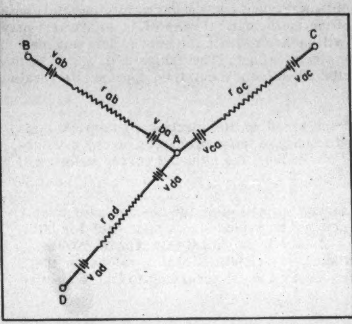

Fig. 2--Electrical analogue for Figure 1

Electrical analogue--Consider now a portion of an electrical network illustrated in Figure 2, containing junctions A, B, C, and D, interconnected electrically in the same relationship as the corresponding survey junctions of Figure 1. Line AB of Figure 2 has electrical resistance r_{ab} proportional to length r_{ab} of Figure 1, and lines AC and AD have resistances r_{ac} and r_{ad}, proportional, similarly to the corresponding lengths of Figure 1. At A, a dc voltage, proportional in magnitude and direction to v_{ba} of Figure 1, is inserted in series on line AB. Similarly, voltages v_{ab}, v_{ca}, v_{ac}, v_{da}, and v_{ad} are inserted in the appropriate places in the lines as shown on Figure 2.

If all junctions in the network are appropriately interconnected, and if all terminals representing fixed bench marks are wired to a common ground, a complex set of closed circuits will be formed, and current will flow through each of the lines or resistances under the combined influence of the various v-voltages. Let the current in AB be i_{ab}, and that in AC and AD be i_{ac} and i_{ad}, respectively. Under these conditions, each junction will have a definite potential e with respect to ground. Let e_a be the potential at A and e_b, e_c, and e_d the potentials, respectively, at B, C, and D. At a fixed bench mark (grounded), the potential e with respect to ground is zero.

By Ohm's Law, $I = E/R$, the current flowing through any line is equal to the drop in potential in the line divided by the resistance of the line. For any of the lines in Figure 2, the drop in potential is the difference of potential between the ends of the line plus the effect of the intermediate impressed voltages. For line AB,

$$E_{ab} = e_a - e_b - v_{ba} + v_{ab} \quad \text{(4)}$$

and the current in AB is

$$i_{ab} = E_{ab}/r_{ab} = (e_a - e_b - v_{ba} + v_{ab})/r_{ab} \quad \text{(5a)}$$

Similarly

$$i_{ac} = (e_a - e_c - v_{ca} + v_{ac})/r_{ac} \quad \text{(5b)}$$

and

$$i_{ad} = (e_a - e_d - v_{da} + v_{ad})/r_{ad} \quad \text{(5c)}$$

By Kirchoff's Law, the net sum of all currents flowing into a junction is zero, or, at junction A,

$$i_{ab} + i_{ac} + i_{ad} = 0 \quad \text{(6a)}$$

or

$$(e_a - e_b - v_{ba} + v_{ab})/r_{ab} + (e_a - e_c - v_{ca} + v_{ac})/r_{ac} + (e_a - e_d - v_{da} + v_{ad})/r_{ad} = 0 \quad \text{(6b)}$$

Comparison of (3b) and (6b) will show them to be identical in appearance, one containing survey quantities and the other electrical quantities. Furthermore, in the development of these relationships, the v-quantities and the r-quantities of the electrical net were made directly proportional to the corresponding quantities of the survey net. It is therefore possible, by proper choice of constants, to make these corresponding quantities in the two equations numerically equal.

It was demonstrated above that there will be as many equations of the type (3b) as there are unknown e-values, and that a unique solution is possible. The same can be readily demonstrated for (6b), which also has a unique solution. But since (3b) and (6b) are identical in appearance, and contain the same numerical values, it follows that the unique solution of one will be identical numerically with that of the other, and that the e-values of (3b) will be identical with those of (6b).

Electrical adjustment--Since the e-values of (6b) and Figure 2 are numerically identical with (or proportional to) those of (3b) and Figure 1, all of the mathematical work of an adjustment may be dispensed with. The r-values of the adjustment will be known from the survey data and may readily be converted to appropriate r-values for the electrical net. The values a, b, c, ..., of the survey may be assumed and the v-values readily determined from them; then appropriate v-values for the electrical net may be determined.

If the electrical net is then properly assembled and wired up, the electrical potentials e may be measured with a suitable voltmeter and converted readily to the appropriate survey e-values. When the latter are properly applied to the assumed abc-values, the adjusted survey values will result.

For a level net, a single set-up and set of measurements will yield the desired adjustment corrections. For a traverse, however, the procedure must be repeated . . . once each for latitudes and for longitudes, latitudes and departures, or X- and Y-coordinates, according to the terms in which the traverse notes have been computed. In the repetition, the r-values for the various lines will remain unchanged, but the v-values must be reset according to the respective closure errors of the coordinates to be adjusted.

Panel

For convenience of use, all the elements of the electrical analogue (the line resistances and the power supplies) are mounted on a single panel together with jacks for making the electrical connections. Until the connections are made for a particular adjustment, there is no electrical contact between individual elements. On the same panel are a number of separate four-jack groups, the jacks of each group interconnected to serve as a single junction point. For fixed points, some additional jacks are tied to a common ground. The wiring of a network for adjustment is accomplished with jumpers made of insulated flexible test leads fitted with plugs to match the panel jacks.

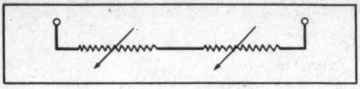

Fig. 3--Line resistance

Line resistances--The line resistances (see Fig. 3), consist of two wire-wound rheostats or potentiometers in series. The sizes are selected so that one may be used for a coarse setting of the resistance and the other for the fine adjustment. The desired resistance is set on calibrated dials on the face of the panel. One of these units is required for each line in the net.

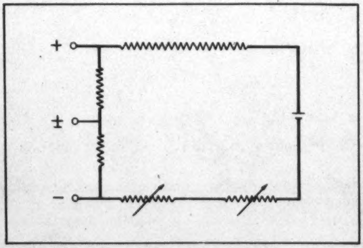

Fig. 4--Power supply

Power supplies--The power-supply circuit is shown in Figure 4. It consists of a battery in series with a fixed resistance to prevent overload, two small bleeder resistances across either of which the desired voltage may be tapped, and two variable resistances for adjusting the tapped voltage.

For the battery, a No. 6 dry cell at 1.5 volts was used in the first test model. It is planned to replace this with a low-discharge type storage battery at approximately two volts in later models. This type battery has remarkably steady voltage characteristics under low loads and is expected to require recharging not oftener than once or twice a year. As in the line resistances, two rheostats are used to give coarse and fine adjustments of the voltage. For large closures the voltage is tapped across both bleeder resistances; for very small closures, it is tapped across only one.

A separate power supply is required for each closure in the net. Because of the variations inherent in the battery voltages, this unit cannot be calibrated. Instead, the closure voltages are set by means of the voltmeter.

Voltmeter

One voltmeter is used to set the closure voltages and to read the correction potentials. Since the critical values of the adjustment (the closures and the corrections) are read on this meter, its sensitivity and accuracy control the precision of the adjustment.

With the standard type resistance voltmeter, a small amount of current is drained from the circuit being measured to produce the deflection of the meter needle. In a circuit of this kind, where the currents are in the milliampere range and the voltages are in the millivolt range, and where accurate readings are required to three significant figures, any appreciable drain of current from the circuit would cause the meter reading to be erroneous. A special "feed-back" meter is therefore needed to measure the voltages without any drain from the circuit. With this arrangement, a voltage is set up in the meter equal and opposite to the circuit voltage to be measured. When the two voltages are exactly balanced, as indicated by a null reading on a galvanometer, the meter voltage is read.

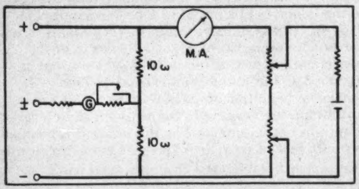

Fig. 5--Lindeck circuit (voltmeter)

Figure 5 shows the diagram of the Lindeck circuit voltmeter. The battery circuit contains a 1.5 volts dry cell in series with a fixed resistance to prevent overload and with two potentiometers (coarse and fine adjustment) for regulating the flow of current through the milliammeter circuit. The latter circuit takes current from the potentiometers and passes it through the milliammeter and two accurately matched fixed resistances. The amount of current through this circuit, and the millammeter reading, can be adjusted by manipulation of the potentiometers. There are three voltage terminals, one at each end of the pair of matched resistors and one between them. In series with the middle terminal is a galvanometer with a fixed resistance to protect it and with another large resistance that may be shorted out for a more sensitive setting of the galvanometer. For any given milliammeter reading, the current through this circuit, and hence the voltage drop across each of the fixed resistors, is known. Since the voltage drop is exactly proportional to the milliammeter reading, the meter may be calibrated in volts-drop across the fixed resistors. Furthermore, since actual voltage is not of particular interest, the meter may even be calibrated in any convenient units, and read as units of closure and of correction.

Since the two fixed resistors are very accurately matched, the voltage drop across both will be the same at all times. If the middle terminal is considered neutral, it may be used together with the upper terminal for measuring positive voltages (with respect to the middle terminal), and with the lower terminal for negative voltages.

In use, the selected terminals are connected to the points between which a voltage (or closure or correction) reading is to be taken. The coarse potentiometer is manipulated until the galvanometer reads approximately zero; then the sensitivity switch is closed, shorting the extra resistance and increasing the needle deflection; the needle is then brought back to the zero position by manipulating the fine potentiometer. The voltage (or correction) may then be read on the milliammeter.

Adjustment procedure

To illustrate the routine of a complete adjustment, the step-by-step operations involved will be outlined.

Data--The basic data are shown on a closure diagram such as that of the level net of Figure 6. This diagram must show each line of the survey in its proper physical relation to all other lines. Near the middle of each line is shown its approximate length, in miles. At each point where one line joins another or a fixed tie, the amount and sign of the closure, in thousandths of a foot, is indicated with an arrow to show the direction of closure. For example, a closure of -089 indicates that the elevation of the junction point as observed on the line containing the arrow is 0.089 foot lower than the assumed elevation of that point. Where no closure arrow appears at the end of a line, the observed elevation of the end of the line agrees with the assumed elevation. The fixed tie points are indicated by small circles.

Equipment--The equipment needed to accomplish the adjustment are: (1) A meter similar to the Lindeck circuit (see Fig. 5) described above; (2) a panel containing at least (a) one pair of rheostats (see Fig. 3) for each line in the net, (b) a power supply (see Fig. 4) for each closure shown on the diagram, (c) a group of jacks, tied together, for each junction, and (d) enough grounded jacks to serve as fixed points and leave at least one extra; and (3) enough jumpers to accomplish the electrical interconnection of all the elements as shown in Figure 7.

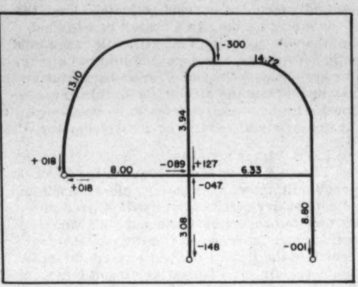

Fig. 6--Level net

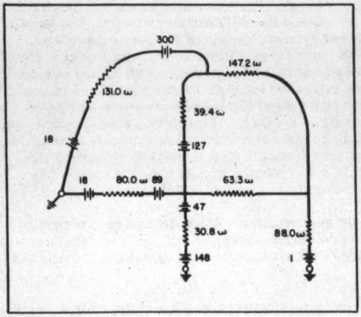

Fig. 7--Electrical analogue for Figure 6

Step 1, line resistances-- The length of each line shown on Figure 6 is set up as a proportionate resistance on one of the pairs of rheostats (see Fig. 3) by setting the appropriate values on the dials. In this example, a ratio of ten ohms per mile has been selected.

Step 2, closures--This procedure is followed for each closure shown on Figure 6. Connect the upper (+) terminal of the voltmeter (see Fig. 5) to the upper (+) terminal of a power supply (see Fig. 4). (If the closure value is very small, use the middle terminal of Figure 4 instead of the upper one.) Connect the middle (±) terminal of Figure 5 to the lower (-) terminal of Figure 4. Using the potentiometers of Figure 5, set the milliammeter reading to the value of the closure. In this example, one unit on the scale is equivalent to 0.001 foot of closure. The galvanometer needle should now be deflected from its zero position. Adjust the coarse rheostat of Figure 4 to bring the galvanometer needle almost to zero. Close the sensitivity switch of the galvanometer, and bring the needle back to zero with the fine rheostat of Figure 4. With the galvanometer indicating zero, the voltage across the terminals of Figure 4 is equal to that indicated on the milliammeter of Figure 5. Disconnect the meter circuit from the power supply and repeat the process for the next closure value.

Step 3, wiring--Using the jumpers, interconnect the jacks of all the appropriate line resistances, power supplies, junctions, and fixed points exactly as called for by the diagram in Figure 6. The completed electrical analogue is shown in Figure 7. Note that where a plus closure is shown at a junction, the plus end of the power supply is connected in the direction indicated by the arrow. The polarity of the connections is critical.

Step 4, adjustment corrections--Connect the middle terminal of the meter circuit (see Fig. 5) to one of the spare grounded jacks of the panel. (The fixed points represent points of zero correction and zero potential.) Connect the plus terminal to one of the junctions of the network. Using the coarse potentiometer, the sensitivity switch, and the fine potentiometer in turn, as described above, bring the galvanometer needle to its zero position. Record the milliammeter reading as the positive correction at that junction. Leaving the middle terminal grounded, move the plus terminal to the next junction and repeat the process.

If the galvanometer needle cannot be brought to zero with the plus terminal connected to a junction, move the jumper from the plus terminal to the minus terminal of the meter and proceed as above. Record the meter reading as a negative correction at that junction.

Conclusions

A small panel, having a capacity of ten lines, ten closures, ten junctions, and ten fixed points has been used for adjusting small nets of levels and traverse. The results, in each case, have agreed exactly with least-squares adjustments of the same nets. Steps are now in process for the construction of a larger panel to handle routine adjustments.

While it has not been feasible to conduct time studies with the equipment on hand, experience to date indicates that it should be possible for one man to adjust a net of 20 to 30 junctions within a few hours. For the adjustment of a traverse net, the latitude closures are adjusted first; then the closures are changed to the proper values for longitude, and the longitude corrections are obtained

Acknowledgements

The idea of the electrical analogue was conceived and developed in the Topographic Branch of the United States Geological Survey. Invaluable assistance in the electrical design and construction was rendered by the Electrical Instruments Section of the National Bureau of Standards. The pilot model of the panel and the Lindeck voltmeter circuit were built at the Bureau, and excellent advice has been offered on the construction of the larger panel. The larger model is being assembled at the Survey.

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THE ENVELOPE METHOD OF ANALYSIS APPLIED TO SURFACE WAVES

William A. Lynch

Abstract--The envelope method of analysis of vibrations is described briefly; examples are given of its application to the main phase of teleseisms and to microseisms, where beating occurs. The importance of its use in the theoretical study of microseisms caused by storms is emphasized, as it readily separates the minor component of the resultant vibration from the major component; the minor component had a period about 14 per cent greater than that of the major and contributed about 45 per cent of the total maximum amplitude of the beat cycle, in the examples given. This component has been ignored heretofore.

The application of the method to the study of traffic microseisms is mentioned.

Introduction--The envelope method of analysis of vibrations is based on principles that have been known for a long time [see "References" at end of paper, HANDBUCH DER PHYSIK, 1927, p. 8, et seq.]. The method has been developed only comparatively recently, however, as the result of wartime demands for the rapid analysis of records of airplane vibrations. It succeeds particularly well when beating occurs, that is when there are two dominant frequencies that differ only slightly; it may be extended to other cases. The present discussion will be confined to the surface waves of seismology and it will be assumed that only two important vibrations are present. MANLEY [1945] gives a complete discussion of the method.

Method--When beats are represented graphically, the curve obtained is approximately sinusoidal, at the same time that the amplitude of the resultant vibration varies approximately sinusoidally. The curve has these important properties: The frequency of the beat cycle is equal to the difference of frequencies of the two components; the frequency of the resultant vibration is that of the major component, the one with the larger amplitude; the separation of the peaks at the bulge is different from that at the waist--if the former is the greater, the period of the major component is less than that of the minor, and conversely, the amplitude at the bulge is the sum of the amplitudes of major and minor components, the amplitude at the waist is the difference of the two amplitudes. By just a few measurements of the beat cycle, therefore, it is possible to obtain full information about periods and amplitudes of the components, which is usually sufficient for practical purposes.

In seismology, phenomena akin to beating occur in the main phase of teleseisms and in microseisms. Periods of these surface waves have been reported many times, invariably, as far as can be discovered, in terms of the major components; the minor components have been ignored completely. If the theory is to be developed, it would seem to be essential that the minor components be included.

Examples--To bring out the importance of the minor component in the main phase of a teleseism, the surface waves of the earthquake of April 2, 1947 were examined. The United States Coast and Geodetic Survey reported that this shock occurred at $05^h39.3^m$; the epicenter was at 1°S, 141°E, off the northern coast of New Guinea. A well defined beat cycle was recorded at $06^h51.5^m$ on all three components of the Galitzin-Wilip seismograph at Fordham University. The separation of the peaks shows that the major component is of shorter period. This is the component that is usually reported. An analysis of the three records is given in Table 1 which shows that the minor component has a period about ten per cent longer than the major and contributes almost 30 per cent of the maximum amplitude of the main phase.

The application of the envelope method to the study of microseisms is of greater importance. Much work has been done in the last twenty years in attempting to show a connection between atmospheric distrubances and microseisms; periods and amplitudes have been measured and their variations related to advancing storms. For a summary and bibliography, see MURPHY [1946].

For a theoretical interpretation, more careful analysis of the traces of the microseisms is required; practically all of the published results for periods and amplitudes are worthless for this

Table 1--Analysis of beat cycle in the main phase of the earthquake of April 2, 1947

Seismograph Component	Vibration		Amplitudes	
	Period of major component	Period of minor component	Major	Minor
	sec	sec	cm	cm
Vertical	18.8	20.6	1.15	0.44
North South	18.6	20.5	2.02	0.79
East West	18.8	20.4	1.15	0.45

purpose. The groups of waves appearing on the record in a microseismic storm have long been classified as beats [MILNE and LEE, 1939]. The envelope method provides a rapid means of evaluating the periods and amplitudes of the dominant components of the trains of waves.

As an example, a group of microseisms was examined from the vertical record of February 21, 1947. A severe microseismic storm had been in progress for several days and the wave trains were exceedingly well defined, the beat cycles being prominent and clear cut. Three successive beat cycles were measured at about $21^{h}23^{m}$. In each case the separation of the peaks at the bulge was the greater, that is, the major component had the shorter period; this is the one that is usually reported. The measurements are given in Table 2.

Table 2--Analysis of three beat cycles in the microseisms of February 21, 1947

Beat cycle	Period		Amplitude	
	Major component	Minor component	Major component	Minor component
	sec	sec	cm	cm
1	4.3	4.9	0.18	0.16
2	4.5	5.0	0.11	0.09
3	4.7	5.3	0.16	0.14

Table 2 shows that the minor component has a period longer than the major by as much as 14 per cent and contributes about 45 per cent of the maximum amplitude of the group. It is the maximum amplitude that is usually reported [LEE, 1934].

Microseisms caused by traffic, especially heavy fast freight trains, are registered regularly at Fordham University on the Benioff short period vertical seismogrpah. They often show beating effects that have been analyzed by the envelope method. The results are interesting as examples of the method but are not sufficiently important to be reported.

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COUNTER CIRCUITS FOR ANEMOMETERS

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Abstract--Applications of electric counters to anemometer circuits, to make frequent ascents of the instrument tower unnecessary, and to give indications in convenient form, suitable for recording or reporting with a minimum of preparatory computation, are here outlined.

Introduction--There is an increasing need in industrial meteorology and in some phases of climatic work for a dependable total wind travel figure, to replace a similar figure obtained by extrapolating the conventional one-minute travel measurement. This need led to an investigation of convenient electrical devices for counting the number of anemometer contact closures during any desired time interval. The time-honored method of climbing the instrument tower and reading the odometer is too time-consuming, hazardous, and inconvenient. From this investigation, a number of workable circuits were developed. A few of those which proved satisfactory after extended field and service tests will be here outlined.

Direct shunt connection--The simplest and most obvious counter connection is a direct shunt across the speed indicator lamp, as is shown in Figure. 1. Unfortunately, this connection is also the least satisfactory of any tried, and usually leads to repeated burnouts of the speed lamp, followed by failure of the anemometer contacts within the first 500 hours of operation. Speed-lamp burnouts are caused by the inductive kick of the counter coil when the anemometer contacts open. Peak voltage produced, when a six-volt counter is used, may exceed 150 (actual measurement). Anemometer contact failure is in part due to sparking from this same cause, and in part to excessive current drawn by the combined loads of the lamp and the counter.

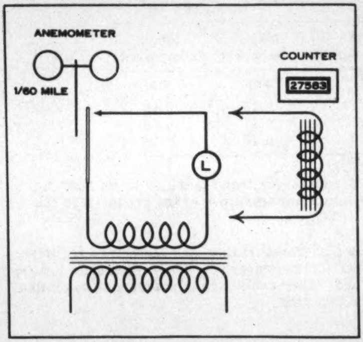

Fig. 1--Shunting of counter across speed indicator lamp

Simple relay circuit--To eliminate lamp and contact failures, a small commercial relay may be interposed between the anemometer contacts and the various indicating devices, as in Figure 2. With this arrangement, the anemometer contacts carry only the relay current, which is within the contact rating. Where a long line is used between the anemometer and the indicators, a conventional condenser-resistor spark-absorber system [see "References" at end of paper, IVES, 1946a], at each end of the line, will prevent radio interference, and will extend the life of the contacts. One set of relay contacts controls the speed lamp, which may be the lamp in a standard ML-117 indicator. Another set controls the counter, which in this arrangement may be operated from any desired current supply. Note the use of a neon lamp to "depeak" the inductive kicks from the counter coil, and the condenser-resistor spark absorber across the relay contacts. Use of these protective devices extends the period between maintenance shutdowns from about 50,000 operations to several million, an important consideration in meterological stations where continuity of record is of paramount importance.

Limiter connection--At stations where wind speed falls below the minimum response speed of the anemometer, the instrument will occasionally stop in "on" position, and the counter coil will be energized for a long period. As counters are designed for intermittent operation, this may damage the coil, necessitating expensive and time-consuming repairs. Thermal damage to the counter coil may be prevented by use of a commercial protective thermostat (similar to "Motor-Kop"), which opens the coil circuit when the windings reach a predetermined temperature. This,

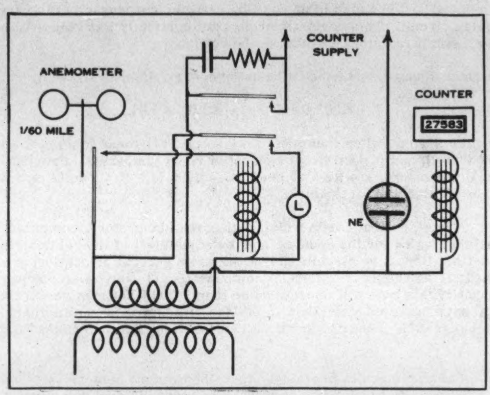

Fig. 2--Simple relay circuit to prevent lamp and contact failures

however, does not necessarily close the coil circuit immediately, and, under certain conditions, the coil-thermostat combination may act as a low-speed oscillator.

By use of a condenser-relay limiter [IVES, 1946b], as outlined in Figure 3, the counter coil is effectively protected from continuous energization and resultant overheating. In this arrangement, relay 1 is operated by the anemometer, and is so chosen that it will not be damaged if the anemometer stalls in "on" position.

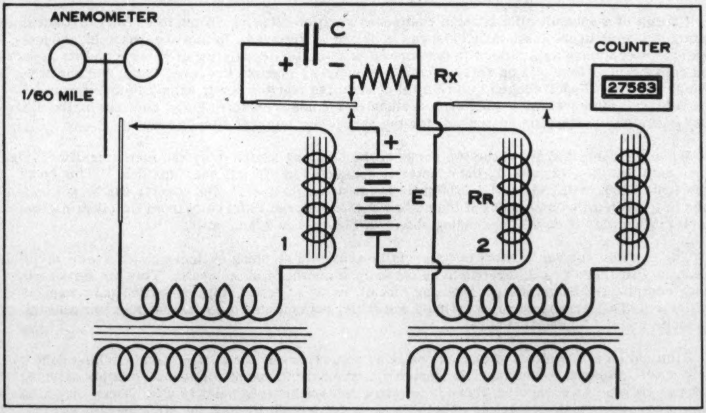

Fig. 3--Anemometer-counter circuit equipped with contact duration limiter

The limiter proper, composed of relay 2 and its electrical associates, functions as follows: When the armature of relay 1 moves to down position, condenser C charges from the battery E, through the coil of relay 2 (Rr). The armature of relay 2 moves down, actuating the counter, and remains down until the charging current of the condenser falls to the drop-out value of the relay.

The armature then rises, and remains in up position until the condenser is discharged and again connected in the relay circuit. This normally occurs automatically when the armature of relay 1 rises, connecting a small resistor, Rx, across the condenser.

Duration of contact closure, and hence of counter energization, is shown by

$$T = 2.303 \text{ Rr C } \log_{10}[E/(R_r \times \text{Id})]$$

in which T = contact closure duration (sec), Rr = relay coil resistance (ohms), C = capacity (farads), E = battery voltage (volts), and Id = drop-out current of relay (amperes). Practical constants, for use with commercial equipment, are Rr = 25 ohms, C = 4000 MF, E = 6 volts, and Rx = 3 ohms or less (value should be as high as practicable).

Values are not critical, so that commercial, rather than laboratory, components may be used. T is set for the optimum value for the counter used by adjustment of the relay spring tension, which varies Id. A number of alternative circuits, using the same general principles, are possible. When properly constructed, using rugged commercial components and "telephone company" workmanship, a limiter circuit of this type will operate more than 1,000,000 times between maintenance shutdowns. Several have operated more than 15,000,000 times without maintenance, final stoppage being caused by disintegration of the relay, whose rated service life was exceeded by a factor of more than three.

Submultipliers--Counter circuits previously described record numerically the number of anemometer contact closures. In many types of work, this necessitates a computation before the recorded data are in usuable form.

Several submultiple contactors, designed to convert the 1/60th mile contact closures of the standard Signal Corps ML-80 anemometer into miles and tenths have been developed and applied [IVES, 1946, c and d]. These employ a six-position ratchet relay, and function quite satisfactorily in short-duration field tests, but are, in general, too noisy and too demanding of skilled maintenance for long-run laboratory work.

Circuit of a submultiplier using a continuous rotation stepping switch to convert sixtieth mile contact closures to one tenth mile closures is shown in Figure 4. In this arrangement, the anemometer operates relay A, which in turn operates a limiter, consisting of relay B and its associated components. Contacts on relay A labelled "spares" operate the speed lamp, and any other devices desired. Upper contacts on relay B connect the counter power supply to the stepping switch circuit momentarily during each anemometer contact closure; lower contacts on the same relay energize the stepping switch coil for the same time interval simultaneously.

When the contact arms of the two banks of the stepping switch (they are mechanically coupled) reach positions 0, 6, 12, and 18, the counter is connected in circuit, and "ups one." This count represents 6/60, or 0.1 mile, if a 1/60 mile anemometer is used. The counter can be conveniently made to read in miles and tenths if the units wheel is colored differently from the other number wheels. When this is done, the reading shown in Figure 4 is 2758.3 miles.

The position number of most commercially-available stepping switches is not evenly divisible by six, so that there is a difference to be taken up somewhere in the cycle. This can be done by a rather complicated automatic progressing circuit, using a second stepping switch and numerous auxiliaries. This arrangement is entirely workable, but contains too many fallible components, and hence will not be detailed here.

Elimination of the effect of excess positions somewhere in the contact circle is best done by use of a self-stepping connection. In Figure 4, a standard 25-point continuous rotation stepping switch is shown. As connected, there is an extra contact between point 18 and "home" position. To eliminate this point, contact 23 in both banks is connected, through the stepping coil and the "off normal" contacts, as a self-stepper. When the contact arms reach point 23, current flows from the rectifier positive, through the contact arms, the off-normal contacts (which are now closed) and to the stepping coil, which is permanently connected to rectifier negative. This energizes the stepping coil, which pulls its armature up. This, in turn, builds up tension in the stepping spring, advances the stepping dog one tooth on the ratchet (attached to the switch arms), and opens the off-normal contacts. This de-energizes the stepping circuit, allowing the stepping spring to pull in the stepping dog, and advancing the switch arms one position. The entire operation takes about 0.05 seconds.

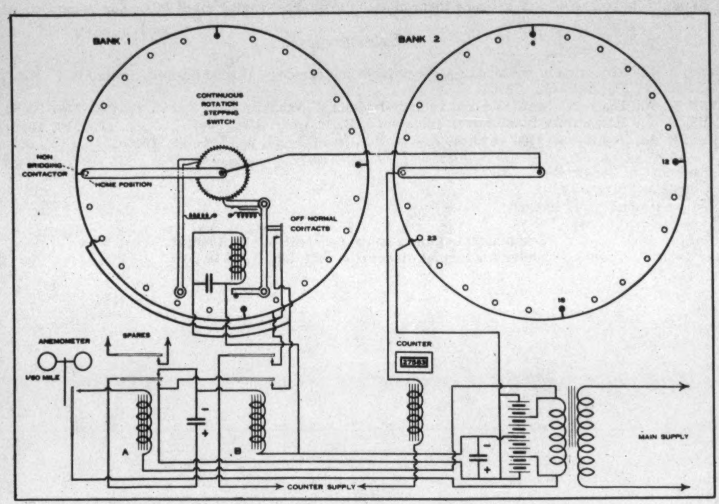

Fig. 4--Circuit of submultiple contactor for converting sixtieths of a mile to tenths of a mile

The same principle can be applied to two points on a 50-point stepping switch. Slight modifications of this action may be necessary with some makes of stepping switch, as some are stepped by the solenoid, instead of by tension of the stepping spring. A medium-sized electrolytic condenser shunted across the stepping coil prevents "buzzering" when the off-normal contacts open. This may be anything from 500 to 5000 mf. If a very large condenser, such as 0.25 farad is used, the circuit is likely to resonate, and to step once when the circuit is energized, and a second time when the supply circuit is broken.

Different contact arrangements can be used to convert anemometer contact closures of other intervals (within reason) into miles and tenths, or other desired figures.

Choice of components--Dependability of operation of all of these counter circuits, and amount of maintenance needed, depends upon the choice of components, and the workmanship used in construction. In very general terms, it has been found that equipment of good manufacture will outlast its factory-rated life even under rather rigorous field conditions. For meteorological purposes, where continuity of record is important, communications-type equipment, designed for long and continuous service with a minimum of maintenance, should be chosen. Purchase of cheap components is, in general, false economy, the entire saving in first cost usually being wiped out by the increased cost of maintenance.

An acute awareness of the number of operations required of the equipment is also desirable. This figure is sometimes quite surprisingly large; for example, with a 1/60th mile anemometer, in continuous operation, and an average wind speed of 10 mph, the annual number of contact closures is 10 × 60 × 24 × 365, or 5,256,000.

Replacement of equipment when it has exceeded its service life, even though it appears in good condition, has been found to be a desirable procedure, as it prevents most "in service" failures. Systematic maintenance and checking of equipment is amply repaid by dependability of equipment and records.

Conclusions--Of the foregoing counter circuits, only the direct shunt counter connection is found unsatisfactory. For recording wind travel in terms of anemometer contact closures, the limiter connection is desirable. When counter figures in terms of miles and tenths are desired, a submultiple contactor will produce them in many instances, saving much laborious computation.

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RECOMMENDED CLIMATOLOGICAL NETWORKS BASED ON THE REPRESENTATIVENESS OF CLIMATIC STATIONS FOR DIFFERENT ELEMENTS

Charles F. Brooks

Abstract--Climatological stations are of two kinds, those established for climatological purposes, and those set up as part of a network for short range forecasting. The closeness of network and choice of sites for stations is not the same in these two classes; in general, the networks for forecasting are closer than those required for climatology. Climatological networks may be most open for insolation, daily maximum temperature, precipitation, wind, and visibility and least open for daily minimum temperature, and snowfall. Temporary stations and climatic profiling tributary to a long established primary station may serve in lieu of many permanent stations within a climatically coherent region. Thus the number of permanent stations can be made as few as one for each zone of one or two degrees of latitude and each zone of 500 to 2000 feet altitude within a large coherent region, each serving some 2000 sq mi in rough or coastal terrain or some 200,000 sq mi in interior plains country. Each zone, however, would require climatic tables for the several types of topographic locations, and detailed maps for completeness. The primary stations would have to be maintained with great care, to guard against errors and changing conditions of exposure.

There are two general types of climatic stations: (1) Those established primarily for the climatological record and local usefulness (temperature, precipitation, wind, cloudiness, local storms), and (2) those primarily for purposes of short-range forecasting. The primarily climatological stations are either the general ones, such as the cooperative stations of the United States Weather Bureau, openly scattered at average intervals of 25 miles (about 500 sq mi per station), or special ones, such as the solar stations (one for about 120,000 sq mi). The primarily synoptic stations are: (1) The general first order weather stations, located at airports, along airways, and off airways; (2) the general second order stations, mostly for the airways; and (3) the specialized stations, such as those in networks for precipitation measurement in connection with flood forecasting or temperature measurement in connection with frost prediction.

The closeness of the networks in each case is determined in the last analysis by the question, How large an area a station, for a particular element or group of elements, can effectively represent for the purpose for which the station was established, and of course how nearly the appropriations can be made to effectuate the ideal? The appropriate closeness must be determined by experiment for each climatic element or even for phases of a single element separately.

For insolation, we now have only one primary station (total radiation on horizontal and on vertical south surfaces and direct and diffuse radiation separately) in 3,000,000 sq mi, one secondary station (total on horizontal surfaces) per 120,000 sq mi, one tertiary (duration of insolation above a moderate intensity) for every 10,000 sq mi, and one fourth order, cooperative station (day clear, partly cloudy or cloudy) for every 500 sq mi. We are far short of determining the distribution of this primary climatological element. In a coastal zone, a station may represent a strip one to five miles wide and 20 miles long, say, 20 to 100 sq mi. In a mountainous region, locations typical of a broad valley, a narrow valley, a south, a north, a west, and an east slope, and a mountain top are needed, and one of each may serve an area of 10,000 sq mi, or one station per 1000 to 2000 sq mi of non-contiguous area. In a plains region, without large lakes or wide rivers, one station per 10,000 sq mi (the present density for third order stations) should suffice.

For temperature, it is necessary to consider separately the daily maxima and the daily minima. The maxima, coming at the time of maximum convective exchange and with maximum wind velocity and mixing, are essentially uniform as to potential temperature over large areas. Thus, one station per 10,000 sq mi seems sufficient, except near coasts and in rough topography, where the densities and locations (non-contiguous) called for in connection with insolation would seem necessary. The minima are very heterogeneous, for they come at a time of stability, which allows local differences in cold air ponding and air drainage to dominate. Thus, one station in each of the following types of locations within each 500 sq mi seems necessary: (1) Hill-top, ridge or prominently exposed shoulder, (a) well above general surroundings, and (b) well below major hills or ridges near by (so that they are likely to be overtopped or flooded by cold air ponding at night); (2) slopes at middle level, (a) steep, and (b) gentle; (3) valley bottoms (a), narrow and with appreciable gradient, (b) broad and with low gradient; (4) towns, small and large; and (5) coasts and islands, the latter tempered by winds of all directions).

For precipitation, the density does not need to be as great for climatological purposes as for flash-flood forecasting, for which a close network is required to catch cloudbursts. The closeness that appears necessary for insolation seems adequate, except that on plains the greater diversity of precipitation than of insolation might call for one station per 5000 sq mi.

For snowfall, including as it does a temperature factor, both with regard to how much snow falls and how fast it will melt on the ground as it accumulates, the density needs to be about twice as great as for precipitation.

For wind, a density in coastal, mountainous, and plains regions similar to that for insolation should be adequate if the anemometers and vanes are exposed well above the general level of the tops of trees or buildings.

For visibility, the requirements are like those for wind, except that in the vicinity of cities observing stations should be located on all four sides as well as within the city.

Temporary stations can establish the differences between the climates at various places and that at a primary, long term station within a climatically coherent area. This can be done in one year or even in a few sampling weeks at such times of the year as would embrace the extremes of temperature and rainfall. The coherent areas are of the order of 10,000 sq mi or even more, say 100,000 sq mi in an interior plains country.

Climatic profiling may be used in addition to learn the rate of change of climatic conditions in different places between one station and another, especially the maximum temperature, minimum temperature, wind, humidity, and water content of snow on the ground (snow surveys).

The primary station, by virtue of comparison with temporary stations and climatic profiling, can then be characterized as to the type of climate within the area that is represented, and thereby greatly increase the precision with which its records can be applied to climatological problems. Except for the bad exposures of sites on buildings, this takes care of the fact that cooperative stations are located where an observer can be found, instead of on some standard type of site.

Climatic networks of the future will be hung on a division of a continent into coherent climatic regions of perhaps 200,000 to 2,000,000 sq mi each, and these into zones of latitudes, one or two degrees each, and of altitude, 500 to 2000 feet each. For each such zone of some 2000 to 200,000 sq mi, climatic tables would be presented for the several types of locations, including as a minimum: Hilltop; south slope; north slope; valley bottom; coast; and city. Maps would provide the complete coverage for the important phases of the elements.

Only one climatic station would be maintained for each zone, and great care would be taken to reduce instrumental and observational errors to a minimum and to maintain unchanging conditions of exposure.

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LARGE-SCALE SYNOPTIC ASPECTS OF FORECASTING FREEZING WEATHER IN FLORIDA

Charles S. Gilman

Abstract--This paper is a study of the relative importance of Alberta and Great Basin HIGHS in producing temperatures at or below freezing in Florida, and the frequency with which freezing temperatures have been preceded by the following types of LOWS: Atlantic Coastal storms, waves from the Gulf of Mexico, LOWS moving through the Southeastern States; deep LOWS in the Upper Mississippi Valley; and those moving through the Great Lakes Region. The most favorable situation for freezing temperatures in Florida is found to be one in which there is an intense HIGH over the Great Basin with an extension into Alberta and with a deep stationary or westward-moving LOW in the Great Lakes-James Bay area.

Introduction--The forecasting of an unusual event, such as freezing weather in Florida is a process conveniently divided into two parts: (1) Recognition of a situation as one in which the event is at all possible, and (2) judgment as to whether or not this particular situation meets the finer requisites for the event to occur. The first part of these processes may be approached from a very broad, macroscopic point of view. Occassionally such a gross recognition may suffice as a forecast, for example, if a person desires to take precautions against a one in ten chance that the event will occur. This might be true in an industry if the cost of preparing for the event is very small compared to the damage which might be incurred. In most cases, however, the weather forecaster must go through both parts of the process.

A logical scheme for investigating the improvement of forecasting would be as follows: (1) An examination of all the situations in which the event has occurred in the past with classification of the large-scale features of all these situations. This gross screening should help to improve the first part of the forecasting process. It is very similar to a typing procedure. (2a) An examination of all data for the period of record to see how often situations similar to those in (1) have occurred, and (2b) contrast of the situations under (2a) with those under (1) to see what additional minute characteristics differentiate situations similar in large-scale aspects but in which the event occurred in some cases and not in others. These two steps may be repeated many times; since each investigation should point out fallacies and limitations in the previous investigation.

This paper will be concerned with only the first of these investigational processes as applied to the occurrence of freezing temperatures in Florida. Moreover, it will be concerned with only the large-scale synoptic aspects. Consideration of initial temperatures in the source region, depth of cold-air currents, the extent on snow cover, and related items are not included.

Method of investigation--Bulletin W (1930) of the United States Weather Bureau gives the dates of all temperatures of 32° F or below for stations in southern Florida. The station at Brooksville, about fifty miles north of Tampa, has, perhaps, as many freezing days as any station. During the years 1899-1930 freezing temperatures occurred there on some 228 days. An index card containing data similar to those shown in Table 1 was prepared for each situation. The maps used were those of the HISTORICAL WEATHER MAPS [see "References" at end of paper]. A situation was considered to be a series of successive days on not more than one of which the minimum temperature was above freezing. Appendix A is a list of the situations studied. From the index cards the data given in the following sections were easily taken.

Summary of situations--The number of situations by months was: October, 1; November, 10; December, 37; January, 38; February, 26; March, 12; and April, 4.

The earliest was on October 29, 1920 and the latest on April 12, 1921. With respect to duration of the situations, the number was distributed as follows: One day, 76; two days, 37; three days, 10; four days, 5; five days, 2; and six days, 3.

Location of HIGH--An attempt was made to see if there was any tendency for freezing temperatures to occur more often with an Alberta HIGH alone, with a Great Basin HIGH alone, or following a period when pressures were high both over the Great Basin and over Alberta or the Canadian Northwest. The breakdown of number of situations according to such a classification is: Great Basin HIGH alone, 56; Alberta HIGH alone, 24; and HIGH over Great Basin and Alberta, 45.

Table 1--Example of data entered on index cards

Event Number 73; Dates, February 3, 4, 6, and 7, 1917

Four days previous--998 mb LOW central Quebec with E-W 1014 mb trough North Carolina to 1003 mb LOW Colorado and 1002 mb LOW Idaho, 1042 HIGH northwestern Alberta and 1050 mb HIGH northern Alaska to Arctic Ocean north of Siberia

Two days previous--968 mb LOW at 5ON5OW, 997 mb LOW New York 1015 mb trough to Gulf, 1057 mb HIGH southern Saskatchewan 1020 ridge to Texas

Previous day--1045 mb HIGH southern Texas, 1041 mb HIGH Utah and 1040 mb ridge Texas to Mackenzie Bay

Summary--Northern Rock and Colorado, LOWS moved eastward developing slightly and pulled down 1057 mb Alberta HIGH

Appendix B gives the particular situations grouped under each location. It is rather surprising to note that in a substantial minority of the situations the associated HIGH comes, not from the Canadian Northwest, but from the Great Basin. Often a LOW pressure area moved across the Prairie Provinces with no HIGH following. However, it will be seen later that the situations of longer duration tended to be associated more often with Alberta HIGHS.

Next a listing was made of the central pressures associated with the various HIGHS four days and two days before the first freezing day. Tables 2 and 4 give the results of this study.

Table 2--Number of situations in which given ranges in central pressure occurred with Great Basin HIGHS, alone

Central pressure		Number of situations with pressure	
from	to	4 days previous	2 days previous
mb	mb		
1050	1054	0	1
1045	1049	0	4
1040	1044	2	9
1035	1039	12	15
1030	1034	17	12
1025	1029	14	9
1020	1026	6	0

Table 3--Number of situations in which given ranges in central pressure occurred with Alberta HIGHS alone

Central pressure		Number of situations with pressure	
from	to	4 days previous	2 days previous
mb	mb		
1060	1064	0	1
1055	1059	1	2
1050	1054	2	4
1045	1049	1	3
1040	1044	8	5
1035	1039	3	4
1030	1034	7	4
1025	1029	2	0
1020	1024	0	2

Table 4--Number of situations in which given ranges in central pressure occurred, Great Basin HIGHS in combination with Alberta HIGHS[a]

Central pressure Alberta		Central pressure in Great Basin in millibars				
		1040	1035	1030	1025	1020
from	to	1044	1039	1034	1029	1024
mb	mb					
1060	1064	0/0	0/0	1/1	1/0	0/0
1055	1059	0/0	0/0	0/0	0/0	0/0
1050	1054	0/0	0/0	0/2	0/1	2/0
1045	1049	0/0	0/1	0/0	2/1	0/0
1040	1045	0/2	0/1	3/2	2/0	1/1
1035	1039	0/1	3/3	1/1	2/1	5/1
1030	1034	0/1	0/2	1/5	3/6	0/1
1025	1029	0/0	0/1	2/0	4/2	0/0
1020	1024	0/1	2/0	1/1	1/0	1/0

[a] In each instance, the value to the left of solidus is based on location of HIGHS four days previous to the occurrence of the freeze, and the one at the right, their locations two days previous.

Several conclusions follow from these data:

(1) No one of the three locations of HIGHS is sufficiently predominant in producing freezing weather for the type *per se* to be very useful as a forecasting tool. Freezing can occur in Florida following periods when the pressure is either high or low over the Great Basin or over the Prairie Provinces. LOW temperatures in Florida can result even from an Alberta HIGH which has a steep east to west pressure gradient on the eastern slope of the Rockies.

(2) Alberta HIGHS which will produce freezing in Florida have, as a rule, higher central pressures associated with them than Great Basin HIGHS which will produce the same phenomenon. This rule, too, is of doubtful validity as a forecasting tool; since the more intense Alberta HIGHS in general have higher central pressures than the more intense Great Basin HIGHS, whether or not they will give freezing in Florida.

(3) There is a slight tendency for pressures to be higher on the second day preceding the freeze than on the fourth day previous. This tendency was to be expected.

(4) Freezing in Florida often follows HIGHS of only moderate intensity.

Associated LOWS four days previous--Next a study was made of the LOWS associated with the various types of HIGHS to see if there were preferred types of LOWS which brought the freezing weather to Florida. These data are given in Table 5.

The most striking thing about Table 5 is the wide diversity of locations of the principal associated LOW. NORTON [1944] pointed out the fallacy of the older idea that a low pressure in Florida must precede the freezing weather. Table 5 shows that the LOW more often comes from the Prarie Provinces or the Great Plains than from the Gulf of Mexico or the Southeastern States. The criteria are rather the intensity of the pressure gradient behind the LOW and whether or not the LOW is in such a position that it will give long-flowing northwesterly winds into Florida. The LOW which most often meets these requirements is a deep, nearly stationary cyclone in the Great Lakes Region. It may, if very deep, be as far north as southern Hudson Bay, or, if very deep and extremety slowly moving, as far east as the mouth of the St. Lawrence. This criterion refutes, at least for Florida, the rule given [U. S. WEATHER BUREAU, 1915] that slow moving LOWS do not produce cold waves.

Track of LOW immediately associated with cold spell--The number of situations in which the LOW followed various tracks is given in Table 6.

More important than the type of LOW is the pressure gradient from the HIGH to the LOW. Table 7 gives the number of situations for various gradients (pressure differences) for the three locations of HIGHS.

Table 5--Number of situations in which the principal LOW to the west was in various locations four days before the first freezing day.

Locations of LOWS	Locations of HIGHS		
	Great Basin	Alberta	Great Basin and Alberta
Prairie Provinces	10	3	6
Great Plains	6	1	12
Mississippi Valley	6	2	8
Great Lakes Region	8	7	3
U. S. East of Mississippi Valley	5	3	3
Arizona and New Mexico	3	3	4
Pacific Northwest	1	0	1
Great Basin	0	2	1
Gulf of Mexico	2	0	0
Texas	4	0	0
Western Atlantic[a]	4	2	2
Quebec	1	1	1
Hudson Bay	2	0	0
Colorado	0	0	1

[a] Easternmost LOW observed

Table 6--Number of freezing situations associated with various locations of LOW centers

Locations of LOW	No. of situations
Developed in Gulf	22
Develped on Atlantic Coast	35
Moved across southern states south of the Ohio River	26
Moved across the U. S. north of the Ohio River	26
Moved along Canadian border	9
Deep LOW northern Quebec or mouth of St. Lawrence	8
Deepened while moving Texas to mouth of St. Lawrence	11

The median pressure difference is slightly more than 30 mb. For four days previously this difference may represent a north to south, south to north, or west to east pressure gradient (high to low). For two days previously all are between west southwest to east northeast and west northwest to east southeast. The extremely small differences are associated with cases where cold air already over Georgia was brought into Florida by a slight backing of the winds over the northern part of the state.

Cold spells of longer duration--Data concerning situations in which minimum temperatures were freezing or below on three to six successive days appear in Table 8.

Table 7--Number of situations having various pressure differences between the nearest definite LOW and the HIGH four and two days before the first freezing day.

Data regarding HIGHS	Pressure differences in millibars					
	10-19	20-29	30-39	40-49	50-59	60-74
Great Basin HIGHS						
4 days previous	8	18	18	5	1	0
2 days previous	2	17	22	8	3	5
Alberta HIGH						
4 days previous	0	7	7	5	4	0
2 days previous	1	2	7	5	3	4
Great Basin and Alberta HIGH						
4 days previous	4	20	14	2	1	0
2 days previous	3	11	13	11	6	2

For these situations of longer duration the Great Basin-Alberta HIGH is the most significant.

These pressures average somewhat higher than those in Tables 2 to 4, but again they are not extremely high.

Table 8--Number of situations in which the HIGHS were associated with cold spells of longer duration

Location of HIGHS	Duration in days			
	6	5	4	3
Great Basin	0	0	0	2
Alberta	0	0	3	5
Great Basin and Alberta	3	2	2	3

Table 9--Number of situations in which the HIGH had various central pressures four and two days before the beginning of cold spells of longer duration[a].

Pressure	Duration in days			
	6	5	4	3
mb				
1060-69	0/1	0/0	0/1	0/0
1050-59	1/0	0/0	2/1	1/2
1040-49	1/0	0/0	0/1	2/5
1030-39	1/2	2/2	3/2	5/2
1020-29	0/0	0/0	0/0	2/1

[a] In each instance, the value to the left of solidus is based on location of HIGHS for days previous to the occurrence of frost; and the one at the right, their locations two days previous

Special features--Some of the features observed frequently were:

(1) Anticyclogenesis in the southern Great Plains of the United States and in Texas. This anticyclogenesis was most noticeable when there was a HIGH of 1030-1040 mb over the Great Basin. Sometimes the eastern HIGH developed rapidly enough to force the cold air into Florida 12 to 24 hours sooner than might have been expected if the HIGH had not developed. Figure 1 is an example of this rapid anticyclogenesis.

(2) A deep LOW becoming stationary or even moving westward in the Great Lakes-James Bay Region with an east to west flow of warm air to the north of the low center. This is the ideal situation for continued northwesterly winds into Florida.

(3) Absence of a strong, slowly-moving HIGH in the southeastern United States as much as four days before the freezing temperatures. This was the most consistent of any of the features observed. No important exceptions were found. Table 10 gives a summary of the pressure in Miami four days and two days before the freezing weather at Brooksville. Most of the cases of higher pressure are associated with anticylones which are already to the east of Miami.

Table 10--Number of situations with various pressures in Miami four days and two days before the freezing temperatures

No. of situations	Pressure in mb				
	1005-1009	1010-1014	1015-1019	1020-1024	1025-1029
4 days previous	0	15	52	56	10
2 days previous	3	22	72	36	0

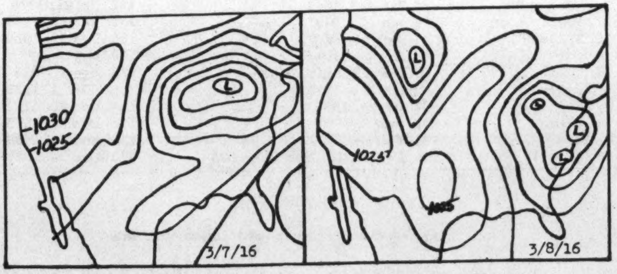

Fig. 1--Rapid anticyclogenesis over southern Great Plains

APPENDIX A

List of situations studied

No.	Date	No.	Date	No.	Date
				95	Mar 6-8, 1920
1	Feb 9, 1899	48	Dec 1, 1911	96	Apr 6, 1920
2	Feb 13, 14, 1899	49	Jan 6, 1912	97	Oct 29, 1920
3	Mar 9, 1899	50	Jan 16, 17, 1912	98	Nov 18, 1920
4	Dec 29, 1899	51	Feb 1, 1912	99	Dec 3, 1920
5	Jan 1-3, 1900	52	Feb 7, 8, 1912	100	Dec 17, 19, 1920
6	Jan 29, 31, Feb 1, 1900	53	Nov 21, 1914	101	Dec 25, 1920
8	Feb 19, 1900	54	Dec 21, 1914	102	Dec 29, 1920
9	Jan 19, 1901	55	Jan 2, 3, 1915	103	Jan 16, 1921
10	Jan 25, 1901	56	Jan 21, 1915	104	Apr 12, 1921
11	Feb 23-26, 1901	57	Feb 9, 1915	105	Jan 2, 1922
12	Mar 6, 1901	58	Mar 23, 25, 1915	106	Jan 13, 15, 1922
13	Dec 17-22, 1901	59	Nov 30, Dec 1, 1915	107	Jan 29, 1922
14	Dec 31, 1901	60	Dec 4, 1915	108	Feb 8, 1922
15	Jan 13-15, 1902	61	Dec 14, 15, 1915	109	Feb 17, 1922
16	Feb 3, 4, 1902	62	Dec 22, 23, 1915	110	Nov 29, 1922
17	Feb 11, 12, 1902	63	Dec 26, 27, 1915	111	Feb 18-20, 1923
18	Feb 19, 1902	64	Feb 15-17, 1916	112	Nov 18, 1923
19	Dec 27, 28, 1902	65	Feb 20, 1916	113	Dec 26, 1923
20	Jan 9, 1903	66	Mar 5, 1916	114	Jan 6, 8, 1924
21	Jan 13, 1903	67	Mar 9, 10, 1916	115	Mar 15, 16, 1924
22	Feb 18, 1903	68	Mar 17, 18, 1916	116	Nov 26, 1924
23	Nov 27, 28, 1903	69	Apr 10, 1916	117	Nov 30, 1924
24	Dec 3, 4, 1903	70	Nov 20, 1916	118	Feb 13, 1925
25	Dec 22, 1903	71	Dec 13, 14, 16, 17, 19, 20, 1916	119	Nov 24, 25, 1925
26	Dec 27, 1903	72	Jan 12, 1917	120	Dec 24, 1925
27	Dec 18, 19, 1904	73	Feb 3, 4, 6, 7, 1917	121	Dec 28, 29, 1925
28	Dec 29, 1904	74	Mar 6, 1917	122	Jan 11, 1926
29	Jan 5, 1905	75	Mar 19, 1917	123	Jan 14, 15, 1926
30	Jan 8, 9, 1905	76	Nov 25, 26, 1917	124	Feb 11-13, 1926
31	Jan 16, 1905	77	Dec 9-11, 1917	125	Mar 14, 15, 17, 1926
32	Dec 23-27, 1906	78	Dec 15, 1917	126	Dec 30, 1926
33	Dec 5, 1907	79	Dec 30, 31, 1917	127	Jan 11, 12, 1927
34	Jan 15, 1908	81	Jan 8, 1918	128	Jan 16, 1927
35	Jan 25, 1908	82	Jan 13, 14, 1918	129	Mar 3, 1927
36	Feb 3, 4, 1908	83	Jan 23, 24, 1918	130	Dec 20, 21, 1927
37	Feb 19, 21, 23, 1908	84	Dec 29, 1918	131	Jan 2-5, 1928
38	Jan 31, Feb 1, 1909	85	Jan 4-7, 1919	132	Jan 29, 1928
39	Dec 27, 1909	86	Jan 12, 1919	133	Feb 19, 1928
40	Dec 30, 31, 1909	87	Feb 11, 1919	134	Dec 23, 1928
41	Jan 23, 1910	88	Apr 2, 1919	135	Jan 7, 1929
42	Feb 14, 1910	89	Dec 16, 18, 1919	136	Dec 1, 1929
43	Dec 2, 3, 1910	90	Jan 3-6, 1920	136a	Dec 4, 1929
44	Dec 8, 1910	91	Jan 15, 1920	137	Dec 20, 21, 1929
45	Dec 21, 1910	92	Feb 9, 1920	138	Dec 24, 25, 1929
46	Jan 5, 1911	93	Feb 16, 17, 1920	139	Nov 27, 1930
47	Feb 23, 24, 1911	94	Feb 27, 28, Mar 1-3, 1920	140	Dec 24, 1930

APPENDIX B

Situations grouped according to the location of HIGHS

Great Basin HIGH alone: Situations 9, 14, 15, 20, 21, 25, 27, 40, 41, 42, 45, 48, 51, 56, 58, 59, 60, 62, 63, 65, 70, 76, 83, 84, 89, 92, 97, 99, 100, 103, 104, 105, 106, 108, 124, 126, 127, 130, 132, 133, 134, 135, 136, 136a, 139.

Alberta HIGH alone: Situations 2, 6, 8, 11, 17, 18, 23, 31, 38, 47, 54, 66, 69, 73, 82, 87, 93, 95, 96, 98, 111, 115, 128, 131

APPENDIX B (concluded)

Great Basin and Alberta HIGHS: Situations 1, 3, 4, 10, 12, 13, 16, 19, 22, 24, 26, 28, 30, 32, 33, 39, 43, 44, 46, 49, 50, 52, 53, 55, 57, 61, 64, 71, 72, 74, 75, 77, 81, 85, 90, 91, 94, 101, 120, 121, 125, 137

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U. S. Weather Bureau,
Hialeah, Florida

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COMPARISON OF PREDICTIONS OF ATMOSPHERIC RADIO NOISE WITH OBSERVED NOISE LEVELS

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Abstract--Two years' data from 16 atmospheric radio-noise measurement stations show sufficient consistencies in the relationship of the noise level and the geographic location of the observing station to indicate that a linear latitude trend approaches a definition of that relationship. The data on 2.5 and 5 Mc during night hours show a fair agreement with the United States Army Signal Corps predictions (RPU-140). An even closer agreement exists between the observed data and a linear latitude relationship for each frequency. The average noise level for the northern hemisphere exhibits a variation, seasonal sine wave with an amplitude of about three units, superposed on a general decreasing trend for the past two years at the rate of about four units per year.

In 1943 the Wave Propagation Committee of the Combined Communications Board, Combined Chiefs of Staff, started investigation of the problems of measurement of atmospheric radio noise. The equipment developed by H. A. Thomas of the National Physical Laboratory, Teddington, England, was approved in August 1944 and went into operation at a few stations by March 1945. By July of that year eight stations were taking measurements. A total of 17 stations, distributed in latitude from 51° N to 41° S, were in operation for all or part of the first two years of the active program (see Fig. 1).

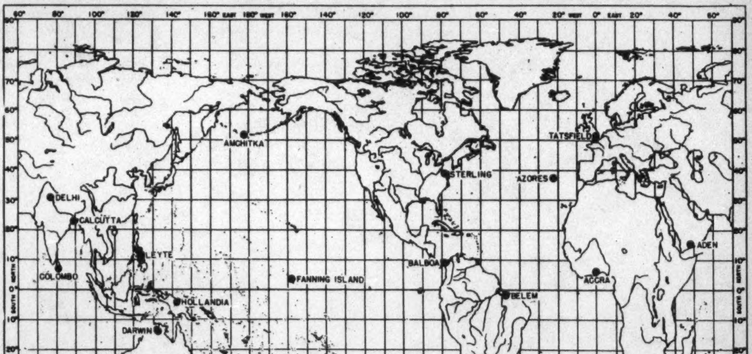

Fig. 1--Locations of stations for measurement of atmospheric radio noise

The method of measurement of atmospheric noise which has been used in the project attempts to determine directly the minimum field intensity required for a given degree of intelligibility in the presence of atmospheric noise. The observations give the field intensity in log microvolts per meter times 20, hereinafter to be called units, necessary for 95 per cent intelligibility of a ten-word-a-minute cw signal with a ten-kc bandwidth receiver. It requires that the cw signal from a keyed standard voltage generator be varied in intensity by means of the voltage generator's attenuator until the operator is able to transcribe just 95 per cent of the five-letter groups in the presence of the noise picked up by a 20-foot vertical antenna. Hourly readings of this minimum required field intensity are taken on frequencies as close to 2.5, 5, 10, 15, and 20 Mc as it is possible to find a clear channel. Set noise level of the equipment imposes a limitation on the natural noise which can be measured. For this reason low measured values of noise, may not represent natural noise but only the lower limit of sensitivity of the equipment. In interpreting the results care was exercised to avoid errors arising from this cause.

The noise data are collected and redistributed by three centralizing agencies: National Physical Laboratory (NPL), Teddington, England; Australian Radio Propagation Committee (ARPC), Sydney, Australia; and Central Radio Propagation Laboratory (CRPL), National Bureau of Standards, Washington, D. C. Research goes forward at the three laboratories, with CRPL conducting investigations of three aspects of the phenomena ... diurnal variation, seasonal variation, and latitude variation.

The most obvious and elementary finding common to the three aspects is that great differences from station to station exist. However, certain systematic characteristics have been revealed, and these characteristics will be discussed in this report.

One of the most useful forms into which the data of the first two years of the project have been cast are shown in Figure 2, which represents daily observations at a fixed hour for one month. The ordinates are the required field intensities in log microvolts per meter times 20, and the abscissas are the numbers of times each intensity occurs during the month on a descending scale. Figure 2 indicates that at Accra at midnight, during October 1945, a level of 37 units was reached but not exceeded once; 33, five times; 30, twice; 27, five times; 23, twelve times; 20 twice, and 17 three times. Readily obtainable from this kind of graph are the month's range for this single hour and the median or other percentile values. The third value from the left, one-tenth of the horizontal scale, with an ordinate of 33 units, for example, is the minimum at or below which 90 per cent of all occurrences fall. This is the upper decile value. This 90 per cent time, 95 per cent intelligibility value is functionally the most useful with which we are at present concerned. In this study, because of uncertainties in lower values previously mentioned, only the values of noise which were reached or exceeded 90 per cent of the time were considered, and averages referred to are averages of those values.

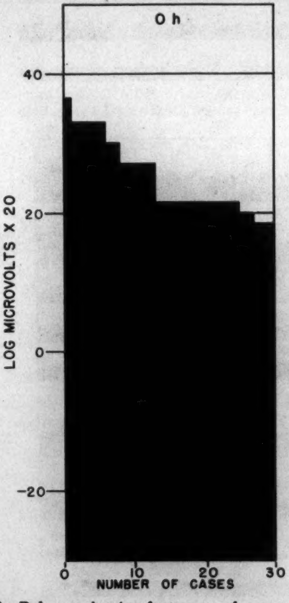

Fig. 2--Polygon showing frequency of occurrence of atmospheric radio noise at various intensities at midnight, Accra, British West Africa, October 1945

In Figure 3, beginning with the hour graphed in Figure 2, 24 successive hourly polygons present a picture of what happened throughout the 24 hours for a given month. This kind of plot shows at a glance the shape of the normal diurnal curve, the magnitude of the diurnal variation, and on what frequencies and at what time of day local storms, characterized by peaks such as those in Figure 3 on 5 Mc at 01^h and 02^h and on all frequencies except ten Mc at 13^h and 14^h, affected noise levels. From enough of these plots some generalizations can be drawn concerning noise at various stations.

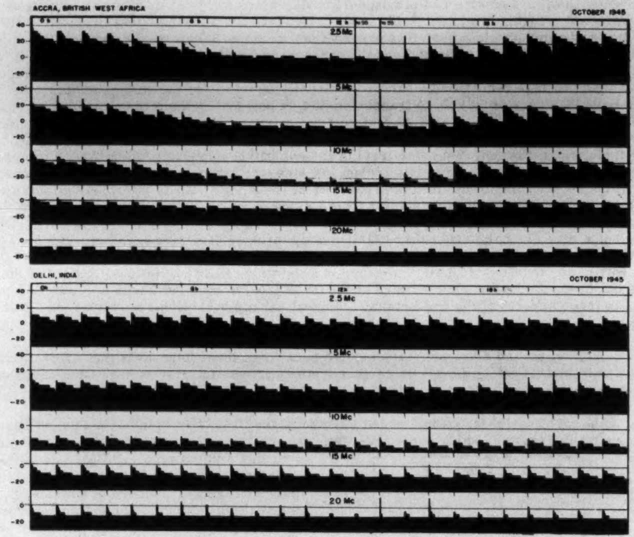

Fig. 3--Polygons showing frequency of occurrence of atmospheric radio noise at various intensities at midnight, Accra, British West Africa, and Delhi, India, October 1945

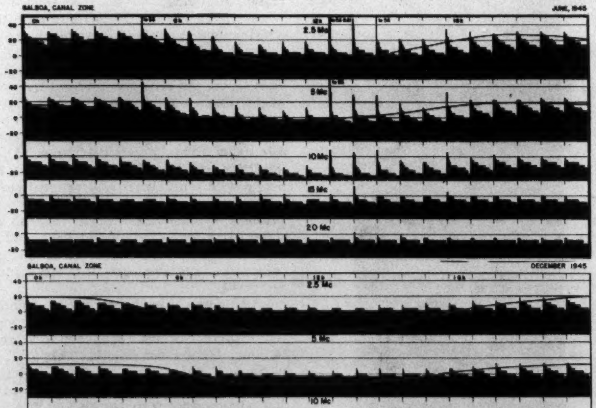

Fig. 4--Polygons showing frequency of occurrence of atmospheric radio noise at various intensities for each hour at Balboa, Canal Zone, June and December 1945

Data from two stations, represented in Figure 3, were selected to give an idea of the nature of diurnal variation in atmospheric radio noise. They show that on 2.5 Mc a drop of about 30 units occurred at Accra from midnight to noon. The times of the most sudden change in level at Accra, about sunrise, which is just before 06^{h} in October, and near sunset, just before 18^{h}, are times at which the greatest changes in ionospheric absorption occur, an effect which is characteristic of all stations, in some degree. At Delhi during the same month, however, it will be seen that the diurnal variation was negligible, being approximately three units as compared with approximately 30 units at Accra.

That there was an even greater drop in noise at Accra than these polygons indicate is at least suggested by the flattening of the monthly range of all frequencies during the middle of the day. The lesser serration of the arrays toward midday may be explained by assuming that the observations were limited by set noise which should exhibit less scatter than natural noise. Decision on this matter must await the installation of improved equipment. The graph for Delhi, on the other hand, shows considerable serration throughout the 24 hours for all frequencies except 20 Mc. Therefore the Delhi observations on those frequencies may be regarded as largely free from limitations of set noise. Contrasted with the Accra data the Delhi data exhibit little diurnal variation.

Figure 4 shows the diurnal curves for June and December, at Balboa. There, also, lack of serration in the graph for December 1945 suggests that the observations for that month were subject to set noise limitations, though the graph for June exhibits sufficient serration on the first three frequencies to indicate that the 90 per cent value was consistently enough above set noise to be significant throughout the day.

The curves superposed on the 2.5 and 5 Mc graphs are the predictions of the United States Army Signal Corps given in their report RPU-140, a revision of the noise curves and charts in the Radio Propagation Handbook of the Interservice Radio Propagation Laboratory. The Signal Corps

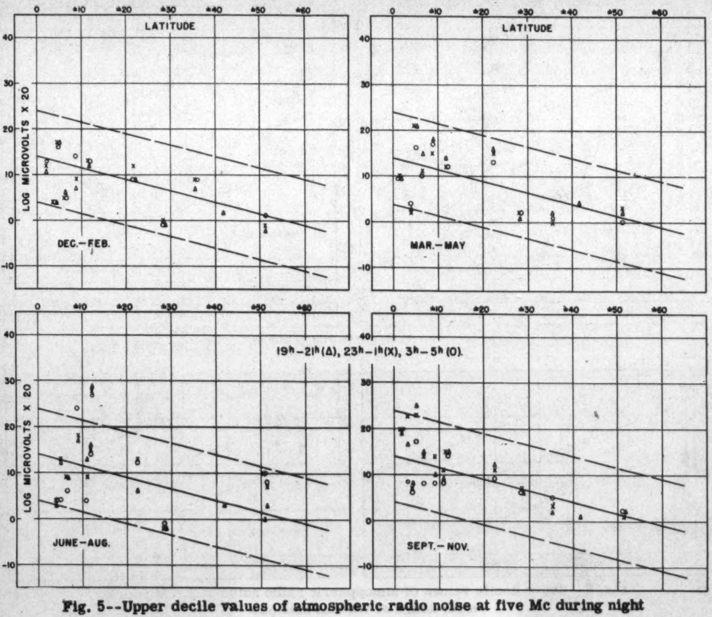

Fig. 5--Upper decile values of atmospheric radio noise at five Mc during night hours at various stations curves represent a value directly comparable with the observed 95 per cent intelligibility 90 per cent of the time. In both June and December at 2.5 and 5 Mc the Balboa observations failed to go as low as the prediction. Again it is necessary to wait until more sensitive measuring equipment is in operation before deciding whether the daytime predictions are in error or the observed values are limited by set noise.

These two months of Balboa data indicate a well-defined seasonal variation with a drop of about 20 units from June to December. Though the supposition of thunderstorms origin of atmospheric radio noise would lead to expectation of a considerable seasonal variation in this direction, no consistent difference of this magnitude was exhibited by the nontropical stations, nor did all tropical stations show a comparable drop. A change of 7.5 units was the average for all stations from June 1946 to December 1946 on 2.5 Mc, but there was a rise of only 4.5 units from December 1945 to June 1946. It appears from this that the seaonal variation may not be as great as has been supposed. Allowing for consistently lowered levels from one year to the next, possibly an effect of solar activity on the propagation of atmospheric radio noise, the average variation which can be attributed to seasonal effects is only of the order of six units. On five Mc about the same seasonal variation in the averages is apparent.

The means of the upper decile values for all data from the various stations at 19^h to 21^h, 03^h to 05^h, and 23^h to 01^h are plotted by seasons in Figure 5 (for five Mc) and in Figure 6 (for 2.5 Mc). The solid lines are the least squares adjustment for latitude dependence, assuming linearity, obtained by lumping together the data for all seasons. Although better fits could have been obtained by separate adjustment for each season the improvement was not considered worth while in view of the greater simplicity of the representation used. As indicated in Figures 5 and 6 the latitudes of the stations have been handled without regard to sign, but where data for southern stations were used they have been plotted in the reverse season. The slopes of the lines indicate a decrease in noise with increasing latitude at rates of 0.24 and 0.36 unit per degree for 5 and 2.5 Mc respectively.

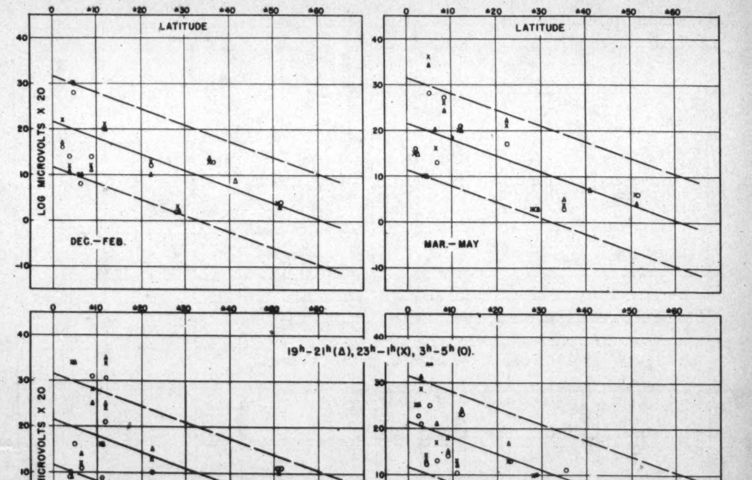

Fig. 6--Upper decile values of atmospheric radio noise at 2.5 Mc during night hours at various stations

The dashed lines in Figures 5 and 6 represent a ten-unit departure from the latitude-variation line and include 93 per cent of all the points. The greatest scatter of points is in lower latitudes.

The least-square lines fitted by individual months to the data of Figure 6 for the 2.5 Mc noise had various slopes and intercepts. The intercepts at latitude 25° N are plotted in Figure 7. In a certain sense these intercepts represent averages of the upper decile values of radio noise for the northern hemisphere. Distinct seasonal and long-term trends are exhibited by the plot, corresponding to a seasonal sine wave with an amplitude of about three units, with its maximum near the June solstice, superposed on a general decreasing trend at a rate of about four units per year. More definite information on the cause of this effect will probably be obtained when the sunspot maximum has been passed and the decreased solar activity produces less absorption. It may be expected that the annual curve of noise level will gradually approach a true sine curve at the time of sunspot maximum and later will reverse its present trend. Similar effects are observed on five Mc, but they are less pronounced.

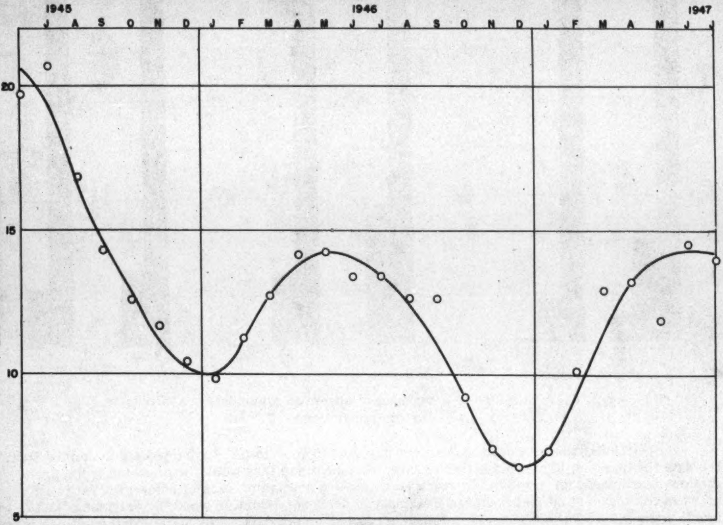

Fig. 7--Trend of monthly average of atmospheric noise at 2.5 Mc, Northern Hemisphere, June 1945 to July 1947

The average values of atmospheric radio noise and the values given by the least square lines of Figures 5 and 6 may be regarded as predictions, and as such may be compared with predictions made in other ways. Such comparisons of predicted and observed values on the 2.5 Mc and five Mc frequencies are shown in Figure 8. The first pair of polygons shows the percentage of observations for the night hours, averaged as before by three-hour groupings, which fall within plus or minus 10, 20, and 30 units of the predictions of the Signal Corps report, RPU-140, calculated for each station. The second pair of polygons represents the same type of comparison assuming that the noise level the world over is 15 units on 2.5 Mc and 10 on five Mc. These "predictions" are about as good as the Signal Corps predictions. The third pair of polygons represents the same kind of comparison, the "prediction" being given by the latitude variation lines in Figures 5 and 6. These results are slightly better than the Signal Corps predictions for 2.5 Mc and five Mc.

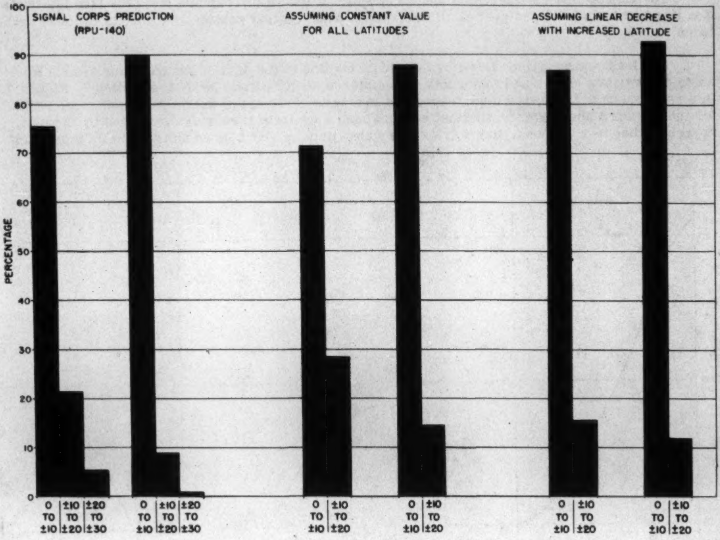

Fig. 8--Percentage of deviations of observed atmospheric radio noise from predictions

Since the parameters used in the first pair of polygons in the Figure were determined from the data themselves, somewhat better results were obtained than would be expected if the predictions were made for regions for which no data were available. It is of some interest to remark in this connection that Southern Hemisphere data, not available when the original adjustments were made, fell close to the values "predicted" from data taken in the Northern Hemisphere. The results do show that the observed world-wide distribution of atmospheric radio noise on 2.5 and five Mc at the hours and stations in question is about as well represented by assuming a simple linear latitude variation as by the much more complicated charts given by the Signal Corps in RPU-140. Improvement would have been obtained had the effects revealed in Figure 7 been taken into account; however, inclusion of them would have involved the use of a considerably larger number of parameters.

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THE CALCULATION OF TIDES IN NEW CHANNELS

J. Van Veen

Abstract--The numerical solution of the large number of simultaneous partial differential equations used in the theoretical design of the Netherlands waterways has previously been done manually at enormous expense of time and money. This paper shows how the same ends may be accomplished by an electrical network analogy.

The calculation of tides has puzzled engineers for generations. When the crude or purely empirical formulas are left out of consideration, LORENTZ [see "Reference" at end of paper, 1926], the discoverer of the electron, was the first to give a satisfactory mathematical solution. His problem was to solve the question of how the tides and currents in the Netherlands waters would be affected by the construction of the Zuiderzee dam. About $250,000 was spent to calculate these tides. This may seem high enough, but it amounts to only 0.05 per cent of the whole cost of the work. The calculation of the Zuiderzee enclosure took eight years, from 1918 to 1926. The formulas used were

$$\left.\begin{aligned} \partial s/\partial x &= -B\partial h/\partial t \\ (1/gbH)\partial s/\partial t &= \partial h/\partial x - ks/bH \end{aligned}\right\} \qquad (1)$$

with notation as indicated in Table 1.

Table 1--Notation in the equations

Notation	Description
s	discharge in cubic meters per second
x	horizontal distance
b	surface width of river-section
B	full width of section
g	acceleration of gravity
k	constant of Lorentz
H	depth at average height of the tide
z	height of average level above datum plane
f	area of cross section
c	coefficient in formula of Chezy
h'	depth at end of river-section
h	depth at beginning of same
s'	discharge at end of section
s	discharge at beginning of section
h.	momentary mean depth in section

These equations can be solved with hyperbolic functions. In a net of channels with say 30 different parts, 60 of these equations have to be solved. Of course many electrical calculating machines and special slide rules can be in perpetual use, but even with these the amount of work is very great. Without these machines it would be almost impossible to deal with the problems.

The Lorentz method had to make the following simplifying suppositions:

(1) The vertical and horizontal tide curves (by this last is meant the currents) had to be considered as simple sine waves.

(2) The bed resistance had to be taken as being in linear relation to the current velocity. This relation is therefore taken to be $R_1 :: kv$, whereas the general accepted relation is and should be $R :: cv^2$ in which c = constant of Chezy. By assuming the total amount of work per cycle of both R and R_1 to be the same, Lorentz found a relation between c and k. Only in this way could he keep his equations linear and therefore solvable.

(3) The breadth and depth of a channel were to be considered as unchanging from beginning to end of any reach.

The elements of incorrectness which were inserted by these suppositions might be deemed too influential to obtain good results. Yet, practice showed that, generally speaking, the new method allowed a satisfactory approximation when sea inlets without fresh water were involved. The mean high water and low water outside the Zuiderzee dam, observed after the enclosure, did not differ much from those predicted.

A detail such as the disappearance of the double high water-crest at Den Helder could not be predicted. Here the method failed rather badly. But the currents in the inlets between the Friesian islands did increase about 20 per cent as was calculated, though superficial observation might have come to the wrong conclusion that these currents would have slackened after the cutting off of the large Zuiderzee area.

In the tidal net south of Rotterdam in which the Rhine and Maas empty, the method could not be used easily. J. P. Mazure of the Zuiderzee Department made some alterations with which the calculation could proceed. The new formulas were

$$\left.\begin{aligned} \partial s/\partial x &= -B\partial h/\partial t \\ \partial z/\partial x &= -(1/gf)\partial s/\partial t + (s/gf^2)(\partial f/\partial t + b\partial h/\partial t) + (s^2/gf^3)\partial f/\partial x - |s|s/c^2f^2R \end{aligned}\right\}\ldots\ldots (2)$$

With these intricate formulas the waterways of Rhine-Maas delta were calculated many times, and the results were satisfying. About ten years practice showed, however, that the calculations took too much time to cope with practical demands. We could calculate one special plan all right, but we could not compare the merits of different plans in a quick preliminary way.

The demands of practice are many and require the knowledge of: (1) The change in height of mean high water, spring high water, and neap high water (for quays); (2) the change in height of mean low water, spring low water, and neap low water (for drainage of the land and towns); (3) the change in height of stormtides (for the height of the storm embankments); (4) the changes in velocity (for the question of silting and scouring, dredging or defence of shores); (5) the change in wave heights (for fixing the height of the embankments); and (6) the changes in salinity (for fresh-water intakes, seepage, and agriculture).

In low countries like ours, this last demand is the most urgent because the damage done by salt is enormous. It might spoil the fertility of the whole western part of Holland.

Because of these demands which make it necessary to predict the future changes within two inches or a few per cent, another method was evolved by J. J. Dronkers of the Research Department for the coast and lower rivers. This method, the so-called "exact" method, used the Fourier series and in this way the non-sinusoidal waves and also the quadratic relation $R :: cv^2$ can be taken into account. Therefore all kinds of abnormal or normal tidal phenomena can be calculated with it to a high degree of exactness. It proceeds from hour to hour, or, if necessary, from half-hour to half-hour.

Of course it takes still more labor than the preceding ones. The Fourier series can be lengthened to any extent, so that the accuracy can be raised to the extent necessity requires. The method does not apply the theory of interfering waves, as do the former less exact ones; it takes the velocity of propagation which natuee presents.

The formulas of this so-called exact method are:

$$\left.\begin{aligned} h' = h &+ |s|sx/c^2b^2h_0^3 + (x/gbh_0)\partial s/\partial t + |s|(\partial h_0/\partial t)x^2B/c^2b^2h_0^3 \\ &- s(\partial h/\partial t)(b+B)x/b^2gh_0^2 + (Bx^2/2bgh_0)\partial^2 h/\partial t^2 \pm (B^2x^3/3c^2b^2h_0^3)(\partial h/\partial t)^2 \\ s' = s &+ Bx\partial h/\partial t \pm |s|(x^2B/c^2b^2h_0^3)\partial s/\partial t + (x^2B/2bgh_0)\partial^2 s/\partial t^2 \end{aligned}\right\}\ldots\ldots (3)$$

The three sets of formulas mentioned above do not differ in principle, only in degree of exactness. Total exactness is not reached of course. But they all lack handiness and quickness, which are essential.

It is all right to have extreme accuracy for our plans which may influence the welfare of the whole country for hundreds of years, but to start with we must compare the possible plans in a quick way. For one plan only (of $100,000,000) about 150 years of man-labor are necessary for calculating the tides.

The latest development is a return to simplicity. When the foundations of hydraulics are reexamined we find that the water currents are akin to electrical currents. So we find that Ohms law $i = e/r$ and the well-known formula of Chezy for water in wide rivers $Q = cbh^{3/2}\sqrt{\partial}$ are analogous if $i :: Q$, $e :: \sqrt{\alpha}$, and $r \approx 1/cbh^{3/2}$.

The conductance of a wide river therefore is $\Sigma\, bh^{3/2}$, which means that depth h is more important than breadth b.

We notice a difference, however, because of the square root-sign before the "potential" or slope α. This difference causes the difficulty, which Lorentz avoided by making a new "constant" k. This k was not a constant, however, because it included a velocity term.

For direct currents, Ohm's law is $i = e/r$, and for alternating currents $i_m = e_m \cos\phi / r_m$ in which e_m, i_m, and r_m are mean values per cycle.

In quite the same way as this formula is deduced we can deduce for alternating currents of water (tides):

$$Q_m = cbh_m^{3/2} \cos\phi \sqrt{\alpha_m} \quad \ldots\ldots\ldots\ldots \quad (4)$$

The cos ϕ of electricity is due to self-induction, the cos ϕ of the tides to inertia. The analogy between electricity and water holds good here.

When we test the simple Equation (4) in our tidal rivers or tidal inlets, making total-flow measurements and accurate tidal graphs, we find that this formula is as good as Chezy's. We tested it 122 times in all kinds of tidal channels, in those carrying fresh water and in those totally filled with sea water.

The value of cos ϕ in tidal channels up to ten meters of depth is about 0.9, or much the same as in electricity. The angle ϕ is the "angle of lag" between the slope graph (the potential-graph) and the current graph. In seas it may be almost nought.

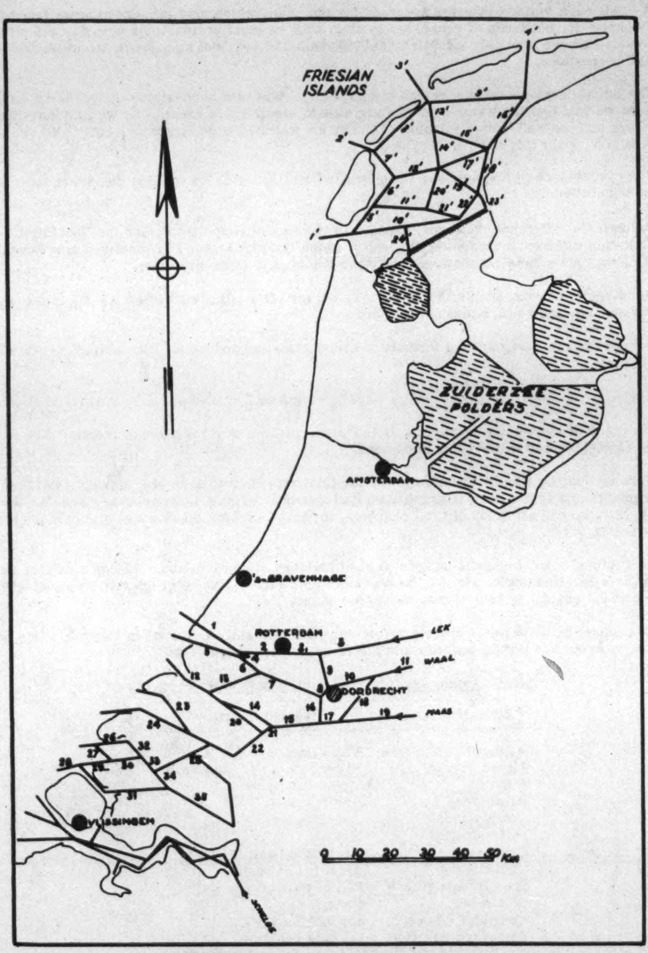
The analogy between water and electrical currents is mainly as shown in Table 2. This analogy can be explained in full, but this would lead us into too much detail.

Table 2--Analogous terms in electric and water currents

Electrical term	Hydraulic term
Alternating current	Tidal flow
Mixed current	River mouths at tidal seas
Potential	Slope, tidal rise
Resistance	Bed friction
Conductance	Conductance
Self induction	Inertia
Condensator	Open tidal basin
Capacitance	Tidal fill of basin
Spread capacitance	Fill of channel per mile
Ohm's law	Chezy's law
Kirchhoff's laws	Kirchhoff's laws
Telegraph equation	Lorentz equation

When the principles of the analogy between alternating currents and tides became clear, the possibility became apparent to imitate our tidal nets (see Fig. 1) by means of copper wires, resistances, self inductions, condensators, and other electrical elements, and use cathode-ray tubes in order to make the tides visible. By using double cathode-ray tubes we were able to see the curves of two vertical or two horizontal tides together in their right relation.

An imitation of the linear net, according to (1) and (2) was made. The results were as good as those obtained by calculation. Figure 2 shows such a model of a tidal river. At the left end an


FRIESIAN ISLANDS
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ZUIDERZEE POLDERS
AMSTERDAM
'S-GRAVENHAGE
ROTTERDAM
DORDRECHT
LEK
WAAL
MAAS
VLISSINGEN
SCHELDE
0 10 20 30 40 50 Km

Fig. 1--Scheme of the tidal channels or network in the Netherlands on which tidal calculations have been made since 1920

alternating current is inserted and at the right end a direct current is used because the tide has died out there. During the war we could not obtain more elements than are shown here, and even now we will still have to wait a very long time to get more.

The so-called exact formulas can also be imitated but here the lack of elements is still more restrictive. This imitation gives the best results and also the quickest because the solution of the

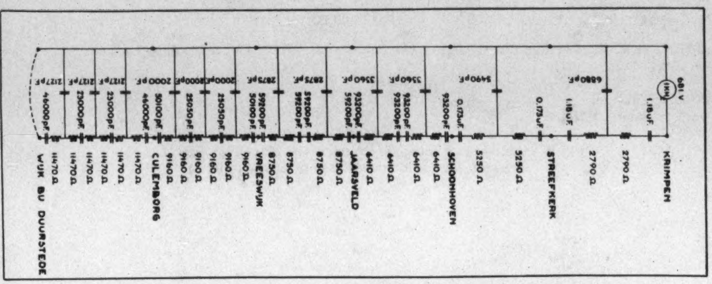

Fig. 2--Electrical imitation in a linear way of the tidal River Lek, length about 60 miles; at the right end an alternating (or tidal) current is inserted, and at the left end a direct one (discharge of river)

linear formulas involves some estimates of the velocities before they are known. The imitation of the quadratic net will need only a small amount of calculation and it gives accurate results (say within two per cent) with non-sinusoidal, natural tide lines and current lines that may be photographed (see Figs. 3 and 4).

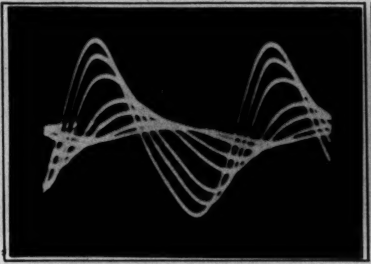

Fig. 3--Kathode-ray photograph of the vertical tides of seven stations on the River Lek, imitated electrically

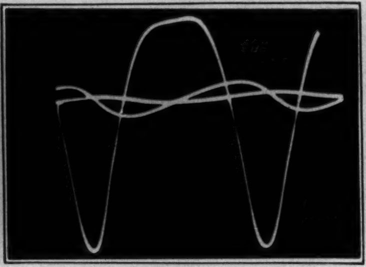

Fig. 4--Tidal streams on three stations on the River Lek, obtained electrically

The electrical imitation is not a real imitation because it does not have widths and breadths. It is more a calculating machine for solving (3), doing the routine work in a very quick and in a very accurate way, because all factors of these intricate formulas are in the imitation, even the term of Bernoulli. The tide changes when it is propagated up-river; the front part becomes steeper and the tide lines become deformed. This same thing occurs, of course, in the electrical model, as Figures 3 and 4 show.

For the electrical layout the items needed are the tidal graphs in the sea before the inlets, the largest, mean, and smallest flow of fresh water down the river, the soundings of all channels and the heights of the banks as far as the water extends at storm tides and, if possible, the constants of Chezy for all different channels. To obtain these constants many tide gauges must be read for several days with chronometers all showing exactly the same time. Of course we can take this constant to be 50 for all channels and be not far from correct, but nevertheless more accuracy is to be preferred. The method can likewise be used for calculating networks of irrigation channels, for braided rivers and also for calculating air currents in mines or underground railway tubes.

Reference

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The Hague, Holland

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THE REFRACTION OF SURFACE WAVES BY CURRENTS

J. W. Johnson

Abstract--When ocean waves, moving through deep still water, encounter a current, moving at an angle with the wave direction, the waves undergo a change in length, steepness, and direction of travel. A theoretical development is given for these factors in terms of initial wave length and direction, and the magnitude of the current. Discussion is given of the action of a coastal current in affording protection against short period waves.

The effect of currents on waves has long been known in a qualtitative way but has been investigated quantitatively, either theoretically or experimentally, only fragmentarily. A paper by UNNA [see "Reference" at end of paper, 1942] has been prepared on this subject and deals with the problem of waves advancing directly into a current, running either with or against the waves. This report deals with another idealized situation, namely, waves approaching a current from the side. The conditions assumed in the latter case do not reduce to those of the earlier report when the angle between the wave crests and the current direction is 90 degrees, for under these circumstances the waves would not enter the current from the side.

There are at least two situations in which the refraction of waves by currents may be of practical importance. At tidal entrances, ebb currents run counter to the waves and increase wave height and steepness, thus adding to the hazards of navigation while flood currents flatten out the waves. Major ocean currents, such as the Gulf Stream, may have an appreciable effect on the height, length, and direction of waves approaching the shore and under some circumstances may cause almost complete reflection.

Quantitative application of the equations for refraction by currents may not be feasible but a combination of theory and observation may prove useful. At each tidal entrance, it may be possible to construct a diagram of limiting surf conditions over the bar and in the entrance channel by using the theory to extrapolate from a few observations of deep water waves and inlet channel currents at times when the bar is impassable. Ship operations would be aided if wave forecasters could include approximate bar conditions in their forecasts, as, for example, that a certain entrance would be impassable for fishing vessels for two hours before and after strength of ebb.

Surface waves in deep or shallow water are refracted by currents to an extent which depends upon the initial wave velocity and direction and the strength of the current. Referring to Figure 1, the wave crest which initially occupies the position ABC progresses to position A'B'C' at a later time. For convenience, let the time interval between these positions be T, the period of the incident wave train measured relative to the point fixed on the bottom. As the point A moves, it is necessary for the crest to be continuous across the discontinuity and

$$C_0/\sin\alpha = u + C/\sin\beta \quad \ldots\ldots (1)$$

$$L/\sin\beta = L_0/\sin\alpha \quad \ldots\ldots (2)$$

For a deep water wave moving relative to the current, $C = \sqrt{gL/2\pi}$ and from (1) and (2)

$$\sin\beta = C_0^2 \sin\alpha/(C_0 - u\sin\alpha)^2$$

if $m = u/C_0$, then

$$\sin\beta = \sin\alpha/(1 - m\sin\alpha)^2 \quad \ldots\ldots (3)$$

The quantity m varies from $-\infty$ to $+\infty$, and α from 0 to 90 degrees. The value m is usually less than one when dealing with ocean waves. The length becomes

$$L/L_0 = 1/(1 - m\sin\alpha)^2 \quad \ldots\ldots (4)$$

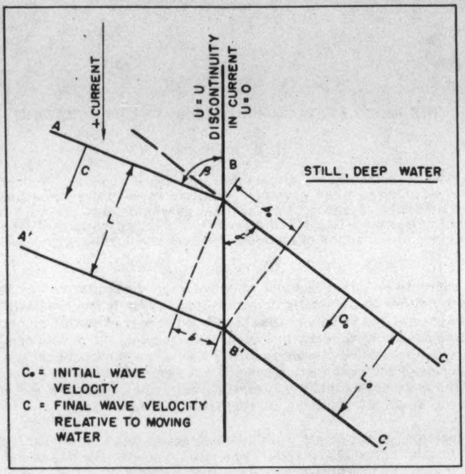

Fig. 1--Relative positions of wave crests before and after refraction by a current

Figures 2 and 3 show values of β and L/L_0 as functions of m and α.

The energy transported by the wave system through a length of crest b_0 must pass through the corresponding length b of the refracted crest. The crest lengths are in the ratio

$$\left.\begin{aligned} b_0 &= BB' \cos \alpha \\ b &= BB' \cos \beta \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The average energy per unit of surface area of a wave is proportional to H^2 and, of the total, one-half is kinetic and one-half potential. Relative to the moving water, energy in the amount $H^2/2$ advances at velocity C and the mass of water has a velocity in the same direction equal to u sin β. The energy transmission balance is then

$$(C_0 b_0/2)H_0^2 = (Cb/2)H^2 + u(\sin \beta)bH^2 \quad \ldots\ldots\ldots\ldots\ldots (6)$$

The change in wave steepness is

$$(H/L)^2 = (H_0/L_0)^2(L_0/L)^2(b_0/b)C_0/(C + 2u \sin \beta) \quad \ldots\ldots\ldots\ldots (7)$$

Using Equations (3), (4), and (5)

$$(H/L)^2 = (H_0/L_0)^2(\cos \alpha/\cos \beta)[(1 - m \sin \alpha)^6/(1 + m \sin \alpha)]$$

or

$$H/L = M(H_0/L_0) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Values of M are shown in Figure 4. The limiting value of H/L is theoretically 0.14 and actually about 0.10.

It is of interest to note that the refraction by currents has two effects on the wave steepness. One effect is on the change in the wave length and the other is on the stretching or the compressing

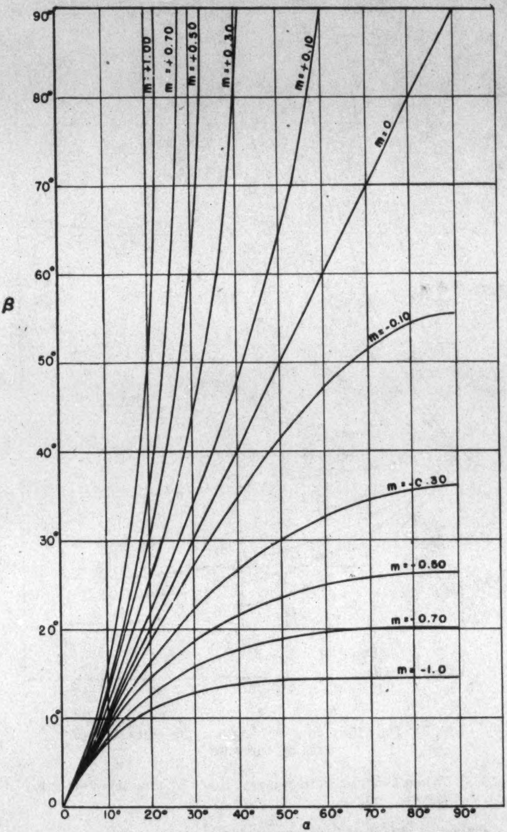

Fig. 2--The effect of wave direction on the refraction of waves by currents

of the wave crest. Thus, for the condition illustrated in Figure 1 the wave length is changed from L_0 to L, whereas the crest of length b_0 is compressed to the length b. These effects in the general case may oppose or add depending on whether the current direction is plus or minus.

It is pertinent now to examine the result obtained when $\alpha = 90$ degrees, thus,

$$\sin \beta = 1/(1 - m)^2$$

β becomes imaginary unless m is negative, corresponding to a current running against the wave direction. The analysis presented assumes waves advancing from the side towards an infinitely long discontinuity in current and the limiting angle, $\alpha = 90$ degrees, does not reduce to the case

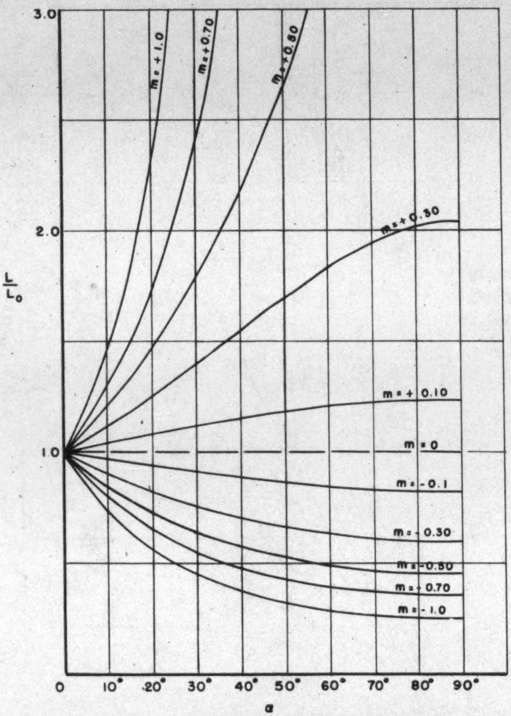

Fig. 3--The effect on wave length in the refraction of wave by currents

treated by UNNA [1942]. When $\beta = 0$ or is imaginary, there is complete reflection of the incident waves at the boundary of the current.

The preceding analysis and that of Unna apply to deep water conditions. A similar but more tedious analysis would result from an analysis of waves refracted by currents in shallow water.

The principal application of refraction methods is to predict the occurrence and height of breakers around a tidal entrance. The direction, height, and period of the incident waves are variable, the bottom contours are curving and usually irregular and the currents are variable in magnitude and direction. Under such circumstances, quantitative forecasting of breakers by purely analytical methods is probably not reliable but a combination of theory and observation should permit construction of reasonably reliable forecasting curves. Reconnaissance by aerial photography should be helpful in constructing such curves.

Figures 5 and 6 are aerial photographs of the entrance to Humboldt Bay taken under practically identical conditions of tide stage and wave conditions except that in Figure 5 the tide was flooding and in Figure 6 the tide was ebbing. Shown on each picture is the stage of tide, magnitude and direction of the current, wave period, wave height and direction in deep water. Figure 7 shows a

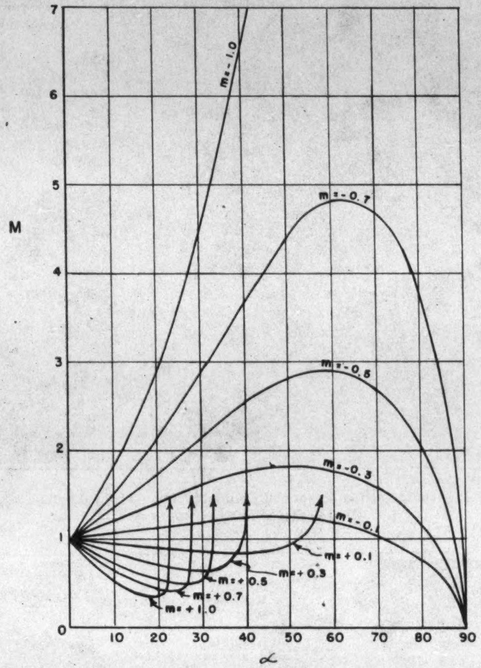

Fig. 4--Steepness factor in refraction of waves by currents

hydrographic survey of the area represented in the photographs. For those cases illustrated in Figures 5 and 6, the depths as well as currents are influencing the H/L of the waves.

Another item of interest with regards to refraction by currents is that a coastal current may offer considerable protection against short period waves; thus, waves generated by local winds may, upon encountering a current discontinuity, increase in steepness, and break. In breaking, the waves lose most of their energy, such that in the area beyond the discontinuity the state of the sea is one of relative calm. References to Figure 4 gives an indication of some of the conditions where such a phenomenon could occur. For example, whether the waves enter an oncoming or a following current they may increase in steepness, and break; thus, when m = +0.1 (a following current) all waves will break for which the incident angle is larger than about 58 degrees. This implies that if waves encounter a current where velocities of two knots exist, for instance, that all waves with a speed of less than 20 knots (periods less than about seven seconds) that enter the current at an angle greater than 58 degrees will break and, therefore, will be unable to cross the current. This probably would be true even though there exists no sharp current discontinuity (as specified in the ideal case shown in Figure 1) and the speed of the current merely increased continuously with the result that m increases from zero to its final value.

These considerations may explain the differences in the state of the sea observed by fishermen off the Washington coast at the "debris line" or dividing line between "green water" along the coast and the "blue water" to the west. A differential of as much as three knots may exist in the current at the discontinuity between the two waters. With a 25- to 40-knot wind blowing a

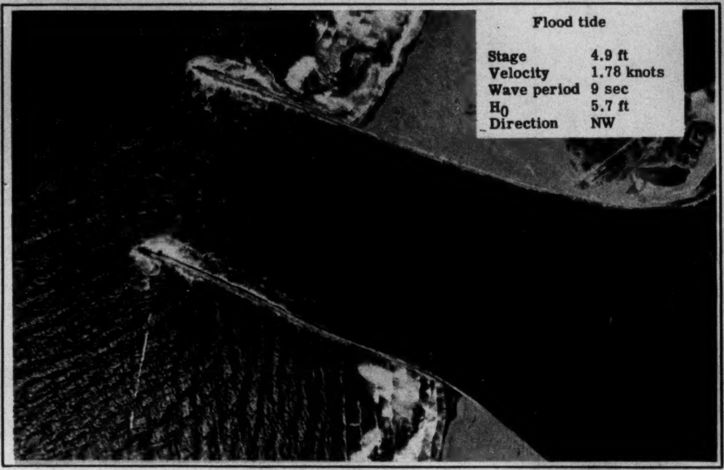
Flood tide
Stage 4.9 ft
Velocity 1.78 knots
Wave period 9 sec
H_0 5.7 ft
Direction NW

Fig. 5--Wave action at the entrace of Humboldt Bay, California at flood tide (United States Navy photograph)

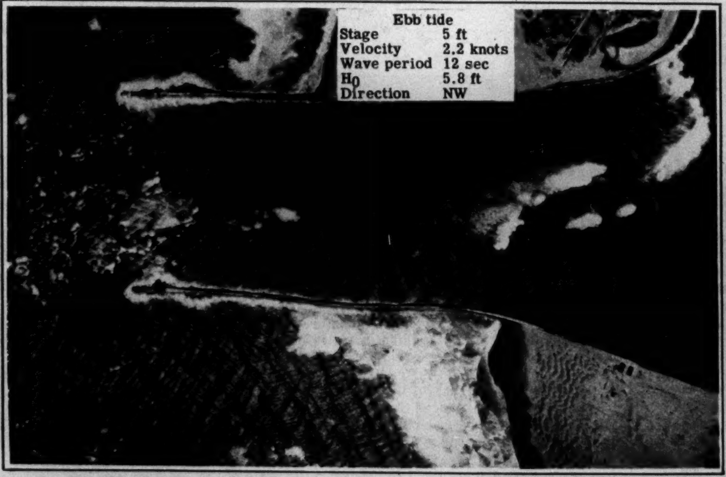
Ebb tide
Stage 5 ft
Velocity 2.2 knots
Wave period 12 sec
H_0 5.8 ft
Direction NW

Fig. 6--Humboldt Bay entrance at ebb tide (United States Navy photograph)

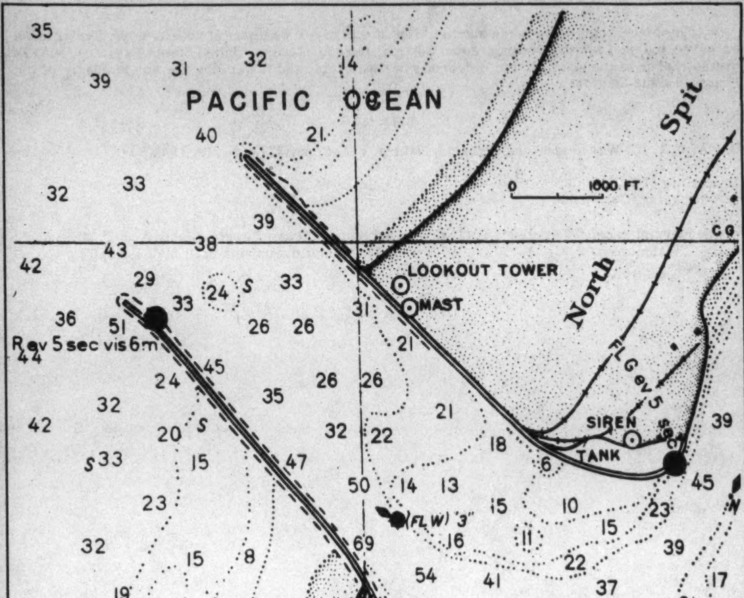
PACIFIC OCEAN
North Spit
South Spit
LOOKOUT TOWER
MAST
TOWER
SIREN
TANK
CG
0 1000 FT.
Rev 5 sec vis 6 m
FL G ev 5 sec
(FL W) "3"
(Qk FL R) 2 BELL
C 3
Cable
N

Fig. 7--Bottom topography at the entrance of Humboldt Bay

rough state of the sea has been observed in the blue water; whereas, the state of the sea on the coastal side is one of relative calm. Only the long period swell was observed to pass on towards shore.

Acknowledgments--The work summarized in this paper was part of an extensive investigation on waves and surf for the Oceanographic Section, Bureau of Ships, United States Navy. M. P. O'Brien was in charge of the work for the University of California, and Roger Revelle was in charge of the Oceanographic Section.

Reference

UNNA, P. J. H., Waves and tidal streams, Nature, v. 149, no. 3773, p. 219, 1942.

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Berkeley, California

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Transactions, American Geophysical Union Volume 28, Number 6 December 1947

SUB-SURFACE PRESSURES DUE TO OSCILLATORY WAVES

R. G. Folsom

Abstract--Measurements of pressure variations with time at or near the ocean bottom provide a convenient means for determination of wave heights and periods. The wave characteristics are obtained from the pressure measurements through application of theoretical relationships associated with oscillatory waves. Laboratory experiments made to investigate the reliability of the theoretically determined correction factors indicate that the theoretical values result in wave heights about ten per cent lower than the corresponding measured values. A brief analysis of irregular waves is included.

Introduction--A series of ocean waves is usually irregular in heights and periods, and are often the resultant of several waves from various sources. Theoretical treatments are limited to regular oscillatory waves, yet many of these ideal wave equations and characteristics are applied without correction for observations to real waves. Figure 1 illustrates the relationships between water surface elevation and time for a sample record obtained in deep water by photographing a special spar buoy with a movie camera. The absolute motion of the spar buoy was less than ten per cent of the wave height.

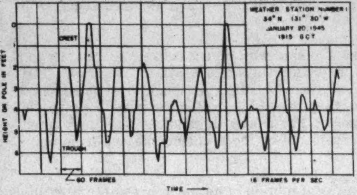


Fig. 1--Elevation changes in water surface with respect to spar buoy in deep water

Ocean waves may be measured by one of three general methods: (1) Surface configurations, (2) pressures at a given depth below the mean surface, and (3) velocities at a given position. Much of the recent work on wave measurements has been made with pressure recording instruments located beneath the surface. The records from these pressure indicators have been interpreted in terms of theoretical relationships in order to obtain the characteristics of the surface wave trains. The available data from these pressure instruments for indicating the degree of correspondence between practice and theory is fragmentary and inconclusive. This laboratory investigation was undertaken to determine the correlation between the actual pressure variations at a given depth and the surface elevation changes in a steady state of oscillation.

Equipment--The experiments to check the theoretical relationships for sub-surface pressures and wave heights were conducted in a laboratory wave channel which was rectangular in shape, one foot wide and three feet deep by about 70 feet in length with the bottom horizontal. At one end of the channel, a straight flap, hinged at the bottom and driven by an electric motor through an eccentric mechanism and Vee belt drive, was used to generate waves. The speed of the flap was controlled to a constant value through comparison with the speed of a synchronous motor operating from an electrical supply of controlled frequency. Regular waves of constant amplitude and period were generated by this equipment. Irregular waves could be generated by operating the flap by manual means when the motor and drive system were disconnected. The other end of the channel was equipped with an artificial beach acting as an energy absorber to dissipate the energy of the waves. A constant depth of water of approximately 2.4 feet was maintained in the channel at the measuring section which was equipped with glass sides for visual observations.

Electric point gages, equipped with fine points and a neon indicating light, were used to determine the wave height at the measuring section. The flashing of this neon light when the point gage was set near the wave crest was used as a means of checking the period of regular waves. The procedure involved the use of a stop watch to time a known number of light flashes. Although not used in this series of experiments, two gages located a known distance apart provided a ready means of determining wave velocities.

The pressure at a point located beneath the surface of the water at the measuring section was determined by a pressure pick-up unit operating with an impedance bridge and recording oscillograph. The equipment was rated by the manufacturer to measure a total range of ten inches of water to an accuracy of 0.1 inch of water, but tests indicated that 0.01 inch of water was possible. The pressure pick-up unit consisted of a metal diaphragm coupled to a permeable slug which was located on the axis of an electric coil. Unequal pressures on the sides of the diaphragm caused a deflection from the equilibrium position which moved the slug relative to the coil and altered the coil inductance. The pressure pick-up unit was mounted on a point gage holder which was supported on a bracket without mechanical connection to the wave channel. The axis of the pressure opening of the gage was perpendicular to the sides of the channel. The oscillograph used was of the string type having four recording galvanometers. Static calibrations were made by adjusting the depth of submergence of the pressure head in still water through operation of the point gage to which the head was attached. Some difficulty was encountered in the stability of the zero setting which tended to drift. Experiments indicated the drift was probably caused by small changes in water temperatures. Different calibration constants were obtained at various times under apparently identical conditions so that it was necessary to calibrate the equipment frequently. The electrical adjustments were of such a nature that amplification could be changed readily; thus, the amplifying factor used in any one setup depended on the magnitude of the pressure fluctuations. Special calibration investigations and use of this equipment indicated that it can be used for laboratory investigations but the sensitivity and required care in operations eliminates the possible application as a field instrument.

Since the channel was equipped with transparent glass sides at the measuring section, the water surface elevation could be observed visually or photographed. A grid system was placed on the glass in order to facilitate the frame by frame analysis of the motion pictures required in the determination of the surface conditions.

Two electrodes were immersed in the water and supplied with direct current electricity in such a manner that the current was proportional to the change in the local water elevation. The record of the current changes was recorded on the oscillograph film. Although these electrodes did not give an accurate picture of the wave surface, they readily indicated the phase relationships of the sub-surface pressures with respect to the changes in surface elevations. The approximate form and the regularity of the wave train were also indicated by the records obtained from these electrodes.

Theory--Considering the two dimensional irrotational motion of an incompressible fluid in a relatively deep channel of constant depth, a theoretical expression may be obtained for the ratio of the pressure variation at a given point below the mean free surface to the equivalent pressure corresponding to the wave height. The solution [see "References" at end of paper, LAMB, 1932] includes the additional assumption that the vertical motion of the water surface is infinitely small. The calculated pressure ratio may be represented by K in the equation

$$K = \cosh\left[(2\pi D/L)(1 - z/D)\right]/\cosh\,(2\pi D/L)$$

where D = mean depth of water in feet; L = wave length, crest to crest distance in feet; and z = depth of pressure instrument from surface in feet. A chart for evaluation of K is presented in Figure 2. These curves cover deep and shallow water conditions.

Experiments--Static calibrations of the pressure measuring equipment were made at the start, during, and at the end of each experimental period. The calibrations were made frequently because the sensitivity adjustment of the amplifier was changed several times in order to increase the amplifications as the depth of submergence of the pressure head increased.

The reproductions of the oscillograph recordings in Figure 3A, illustrate the type of record resulting for a train of waves of constant period and amplitude. The current trace at the top of the record was obtained from the electrodes and indicates the time and approximate magnitude of the surface changes. The middle curve of the diagram indicates the pressure changes occurring at the position of the pressure pick-up unit. The breaks in the bottom straight line indicate the time axis, each break showing a one-third second interval. Irreglar breaks in this time line are used as a code identification of the film record. For regular waves, the curve obtained from the electrodes is in phase with the curve obtained from the pressure pick-up unit, thus showing the correlation of phases for underwater pressure and surface elevation changes.

Three methods wereavailableto determine the actual wave heights and periods. These were (1) measurements with the electric point gage and stop watch, (2) the oscillograph record obtained

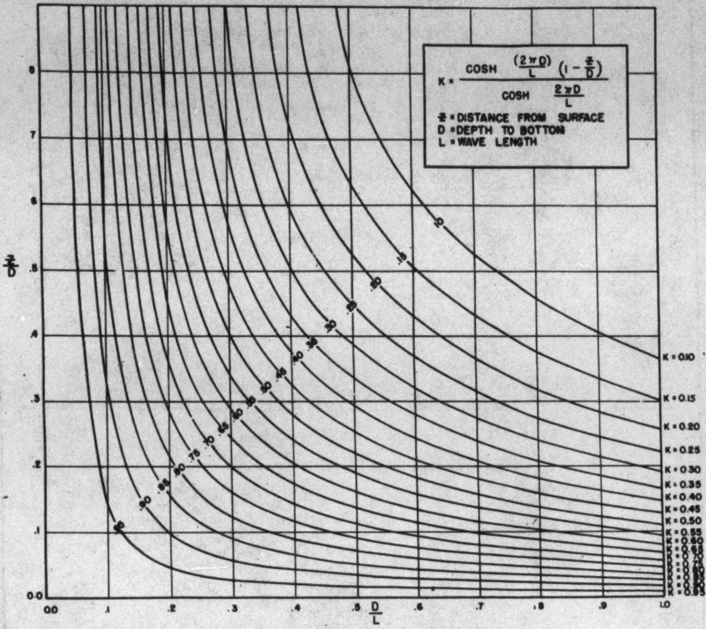


Fig. 2--Calibration curves for constant K

from the pressure pick-up unit, and (3) the 16 mm movies. For regular waves the point gage determinations served as the basis of comparison, the 16 mm movie records being used as an approximate check only. The results of the investigations for regular waves are tabulated in Table 1.

Table 1--Tabulation of experimental and computed results

Run no.	D/L	z/D	Point gage	16 mm film	Equiv. pressure	Difference[a] low	Remarks	K
			ft	ft	ft	pct		
6-29-e	0.82	0.21	0.340	0.328	0.304	11	. . .	0.34
6-24	0.58	0.42	0.274	. . .	0.289	6 (high)	b	0.22
6-29-m	0.52	0.42	0.221	0.222	0.187	15	. . .	0.26
6-29-d	0.47	0.21	0.367	0.361	0.329	10	. . .	0.54
6-29-U	0.38	0.21	0.430	. . .	0.410	5	b	0.62
6-29-v	0.36	0.63	0.392	0.377	0.371	5	. . .	0.29
6-29-c	0.35	0.21	0.322	0.323	0.296	8	. . .	0.64
6-29-K	0.29	0.21	0.352	. . .	0.322	9	b	0.70
6-29-b	0.27	0.21	0.203	0.188	0.175	14	. . .	0.72
6-29-u	0.27	0.63	0.334	0.359	0.315	6	. . .	0.43
6-29-w	0.22	0.63	0.265	0.25	0.287	8 (high)	c	0.53
6-14-1	0.79	0.42	0.319	. . .	0.284	11	b	0.13
6-14-2	0.79	0.42	0.271	. . .	0.238	12	b	0.13
6-14-3	0.79	0.42	0.239	. . .	0.205	14	b	0.13
6-14-4	0.79	0.42	0.170	. . .	0.151	11	b	0.13
6-14-5	0.79	0.42	0.128	. . .	0.113	12	b	0.13
6-14-6	0.79	0.42	0.076	. . .	0.069	9	b	0.13

[a] Per cent difference in the equivalent wave height from the pressure record with respect to the height determined with the point gage. [b] For these runs D was not measured but channel operated with water level approximately at reference line. [c] Calibration data were poor.

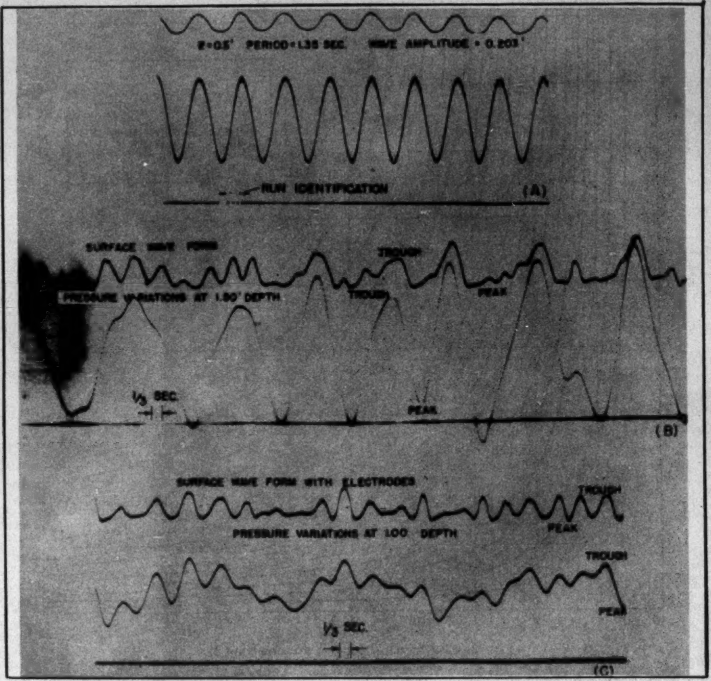


Fig. 3--Typical pressure records of waves in a rectangular channel

The pressure method of measurement of wave height makes use of the amplitude of the subsurface pressure variation at a given point and the theoretical coefficient, K, from Figure 2. In order to facilitate the calculations, Figure 4 was prepared to give the theoretical relationships between wave length and period for a water depth of 2.4 feet. Using the experimentally measured period, Figure 4 gives the corresponding wave length, which combined with the depth of water and submergence of pressure pick-up unit makes it possible to use Figure 2 to compute the coefficient K and the corresponding surface wave height from the measured pressure difference.

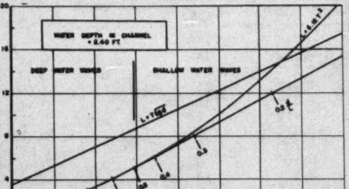


Fig. 4--Theoretical relationship of progressive waves in a long rectangular channel

Analysis of the quantities of Table 1 shows the equivalent wave height computed from the pressure difference to be lower than the height measured with the point gage. On the average, the equivalent wave height is about ten per cent lower than with the point gage measurement. The wave heights determined from the 16 mm film varied slightly (both high and low) from the values measured by point gage, the maximum deviation in eight comparisons being less than seven per cent. On the basis of this correlation, heights as measured from 16 mm films were used as a standard of comparison for irregular waves.

Two sets of irregular waves were investigated, runs R and T. The wave flap was operated manually in such a way that the resulting wave consisted of a long period oscillation with a superimposed short period oscillation. Although the period between waves of each basic train was about constant, no especial attempt was made to control wave periods or heights. Portions of the oscillograph records are reproduced in Figure 3 (B and C). The important characteristics of these waves are summarized in Table 2.

Table 2--Average characteristics of series of irregular waves

Run no.	Average period		D/L		z/D	K		H[b]		No. of waves		Range of periods			
												Long		Short	
	Long	Short	Long	Short		Long	Short	Long	Short	Long	Short	Max	Min	Max	Min
	sec	sec						ft	ft			sec	sec	sec	sec
R	3.9	0.68	0.072	1.03	0.416	0.94	0.08	0.07	0.13	8	41	5.8	1.9	0.97	0.18
T	2.7	0.67	0.106	1.08	0.625	0.84	0.01	0.19	0.12	9	42	3.8	1.95	1.45	0.24
R'[a]	5.1	. . .	0.056	. . .	. . .	0.96	. . .	. . .	. . .	12	. . .	6.6	1.9	. . .	. . .

[a] R' are values obtained from the complete oscillograph record which was about twice the duration of the moving picture record.

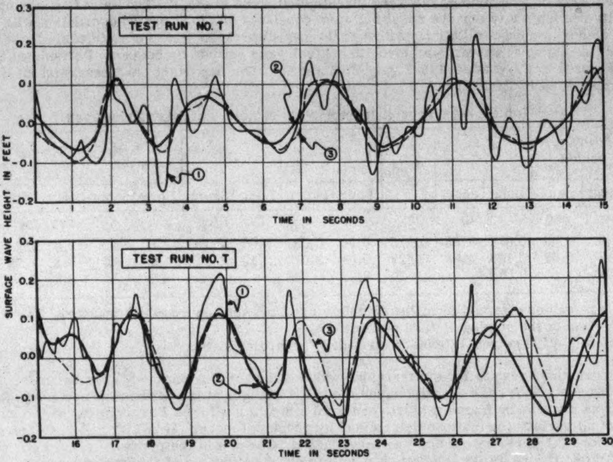
[b] Average wave height, H, crest to trough of preceding wave.

The combined results for the irregular waves are shown in Figure 5. Three curves are included. Curve 1 shows the actual surface elevation changes at the measuring section as determined from a frame by frame analysis of the 16 mm films. Curve 2 is the mean of the envelopes of the actual surface fluctuations determined by graphical means [MANLEY, 1945, Chapter IV] and drawn before the pressure record was investigated. Curve 3 is the pressure record corrected by the coefficient K (see Table 2) associated with the average period of the long period waves to give the calculated surface changes. The individual wave periods were not used since the effects of time lags in dynamic pressure changes is unknown. The coefficient based on the average period is considered more representative. (Run R is the first half of Run R'. The average period for the long wave train is different for the half and whole duration of recording, the resulting coefficients being 0.94 and 0.96 respectively. The larger magnitude was used in plotting Figure 5.)

Since the pressure pick-up unit is placed beneath the mean water surface, the short period waves will have proportionally less effect on the measured pressure variation than the long period waves. In other words, the water tends to act as a mechanical filter to reduce or eliminate the pressure oscillations caused by the short period waves. Run T illustrates this filtering action because Curves 2 and 3 for both runs nearly coincide. The product of K and the true wave height of the short period wave gives the magnitude of the surface wave height that would be shown in Figure 5. For Run T, K = 0.01 and height is 0.12 feet, thus the surface wave height in the diagram would be about 0.001 feet, a magnitude too small to be noticeable

An inspection of Run R of Figure 5 demonstrates a partial filtering of the short period waves (0.68 sec, 0.13 ft, and K = 0.08) with respect to long period waves (3.9 sec, 0.07 ft, and K $\cong$ 0.94) when the submergence of the pressure pick-up unit is less than for Run T (z/D of 0.416 versus 0.625). The product of K and the wave height for the short period waves shows that the surface wave heights in Figure 5 should be about 0.01 ft, a height of appreciable magnitude in comparison with the long period surface wave height of 0.07 feet. In this case theory and experiment show that the short period waves have not been eliminated from the pressure record as occurred in Run T. The results in Figure 5 show the type of records and data that may be obtained from pressure diagrams at submerged depths for irregular surface waves (see Figure 6 for an ocean wave pressure record). The explanation is not complete since the variations in Curve 3 with respect to Curve 2 of Run R are greater than indicated by the theoretical calculations. When the short period effects are small with respect to the long period results, the short period data are masked from the pressure records. When the short and long period results are of the same order of magnitude, some type of mutual interaction appears to take place. This latter situation is not clearly understood.

Discussion and conclusions--For 17 cases of regular oscillatory waves, the equivalent wave heights based on sub-surface pressure differences were about ten per cent lower than the corresponding measured surface wave heights. The values of the coefficient K for these waves varied from 0.12 to 0.72. From a study of the few field data available from instrument installations near shore, a similar difference of about the same magnitude has been shown to exist. The discrepancy



COMPARISON OF ACTUAL SURFACE WAVES TO SURFACE WAVE COMPUTED FROM PRESSURE VARIATIONS AT 1.5 FEET DEPTH

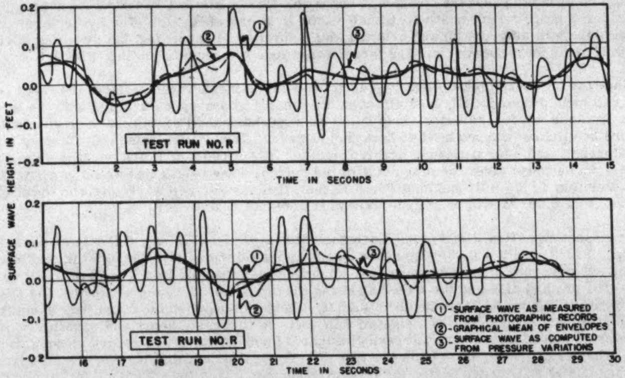


Fig. 5--Comparison of actual surface waves to surface wave computed from pressure variations at 1.0 feet depth

is associated probably with the limitations of the theoretical development (no viscosity and waves of infinitely small amplitude).

Two series of irregular waves were investigated in detail, each series being composed of one long period and one short period wave train. In Run R, the short period train had a wave height of nearly twice that of the long period train. In Run T, the short period wave heights were about two-thirds of the heights for the long period train. Due to a combination of relative wave periods and heights with the submerged position of the pressure measuring unit, theory and experiment demonstrated the lack of appreciable short period pressure variations in the submerged pressure record for conditions of Run T. In Run R, the combination of values was such that both short and long period waves produced appreciable variations in the pressure record, the experimental magnitude of short period pressure differences being greater than indicated by the theoretical results.

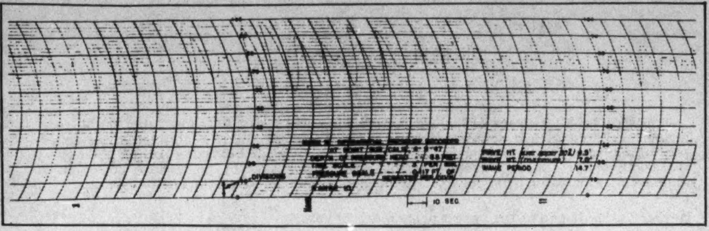


Fig. 6--Pressure record caused by ocean waves

These experiments showed the type of results to be expected from underwater recording pressure units for measurements of wave heights and periods. Under properly selected conditions, long period wave (swell) characteristics may be separated and measured adequately.

Acknowledgments--This investigation was part of an extensive series of experiments on waves for the Bureau of Ships, United States Navy.

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GEYSERS OF ICELAND

Tom. F. W. Barth

Abstract--All geysers of Iceland, active and extinct, are listed in Table 1; the geographical distribution is shown by the map, Figure 1. Boiling is restricted to the upper part of a geyser sytem; deeper down the temperature is far below the boiling point for that depth and pressure. Geyser eruptions are not provoked by super-heat, but by the displacement of water by vapor and spring gasses as they rise in narrow channels.

Geyser action is one of the rarest phenomena of nature.

In Iceland several thousand individual hot springs are known, but very few show geyser action. A conservative estimate indicates that there are today about 30 active geysers, or less than one per cent of the total number of hot springs.

In the Yellowstone National Park hot springs are not as numerous as in Iceland; nevertheless there are at least 200 geysers, corresponding to about ten per cent of the total number of hot springs in the Park. Thus geyser action is much more common in the Yellowstone Park than in Iceland.

The geysers of Iceland have never been accurately counted, and a list of the active geysers is not easy to compile. In the first place the number is not constant; in the course of time active geysers will die, and new ones will form. Secondly, many hot springs are located in such remote and inaccessible regions that decenniums may elapse between each time they are observed; geysers may exist that have never been seen or reported.

The list shown in Table 1, the first of its kind, is believed to correspond approximately to the conditions of 1940. To be brought up to date it should be supplemented and revised.

In order to give a survey of the geographical distribution of the geysers of Iceland Figure 1 was prepared. The numbers on the map correspond to those in Table 1 and will facilitate the location of the several hot springs. It is worthy of note that all active geysers are in the zone of recent volcanism that extends across Iceland from SW to NE. None occurs in the Tertiary basalts on either side of the volcanic zone.

Geysers have a tendency to cluster forming more or less well defined "geyser areas." The active geyser areas are marked with solid circles on the map. It is seen that in southwestern Iceland, (in the counties Biskupstungur and Grimsnes), three black circles lie close together (nos. 10, 35, and 61). These three areas together with the extinct areas at nos. 18 and 55 might be considered as one large geyser area. Likewise nos. 511 and 478 might be grouped together. Thus considered there are today only five active geyser areas in Iceland.

Such areas undoubtedly correspond to situations particularly favorable for geyser action, for within the areas a high percentage of the hot springs are geysers. For instance, Hveraveller (no. 478) in Central Iceland, an area of intense thermal activity, comprises about 30 hot springs including seven active geysers, and a similar number of dead ones.

What are the conditions causing geyser action in these areas? In a general way one can say that the probability of a hot spring becoming a geyser is a function of b, c, t, and the topography and surface conditions; b is the volume of spring gases, c the volume of water discharged per second per unit section; t is temperature.

In Iceland at large the probability ratio is low (less than one per cent), but within the several geyser areas as much as 25 per cent of the total number of hot springs may exhibit geyser action.

Although the life of an individual geyser may be ephemeral, the geyser areas as such have persisted for centuries. For instance, Reykir in Ölfus (no. 77) has existed as a famous geyser

Table 1--Geysers in Iceland in 1940

Geyser area		Active geysers	Dead geysers
Name	No.		
Haukadal	10	Geysir Otherrishola Litli Strokk Smidur	Strokk Litli Geysir Blesi Konungshver Stjarna
Vindás on Thjorsá	18	......	Two dead geysers
Hruni	35	Básahver, N.	Básahver, S. Laugarhver
Middalur	55	.....	Laugarvatn Utey
Torfastadir	61	Reykholtshver	Sydri Reykir
Reykir in Őlfus	77	Gosi II Bogi I Bogi II Gryla IV 0[a] VI u[b] Svadi Badstofuhver Hveramvahver	Hveragerdi, several dead geysers Gosi I Litli Geyser Tungarshver
Cape Reykjanes	216	......	Sea Water Geyser
Reykhólar	296	......	Kraflandi
Isafjardardjúp	327	......	Two dead geysers at Reykjanes
Borgarfirdir	264	Sturlureykir Kopareykir Dynkur	Deildartunga Árhver Skrifla Strokk
Reykjahverfi	415	Ystihver Uxahver Odiphtong	Sydstihver
Hveraveller	478	Brædrihver A Fagrihver Goshver "N"[b] "P"[b] "Y"[b]	Brædrihver B Eyvindarhver Geyser at Djúpihver Gamli Strokk F[b] V[b]
Beljandarkvislar	511	One active geyser	....

[a] Designation of THORKELSSON [see "References" at end of paper, 1930].

[b] Designation of HUMLUM and TUXEN [1935].

area as long as historical records go, but the individual geysers have suffered radical changes. A new geyser was formed in 1597. Later, the earthquake of 1789 caused great changes in the existing geysers. Then in 1896 another new geyser was formed accompanied by much noise and the rush of great quantities of steam, mixed with dirt, clay, and rock fragments which were shot six to seven hundred feet into the air. The force of the geyser decreased very soon and after two days the jets were only ten feet high. After ten days of activity the geyser was dead.

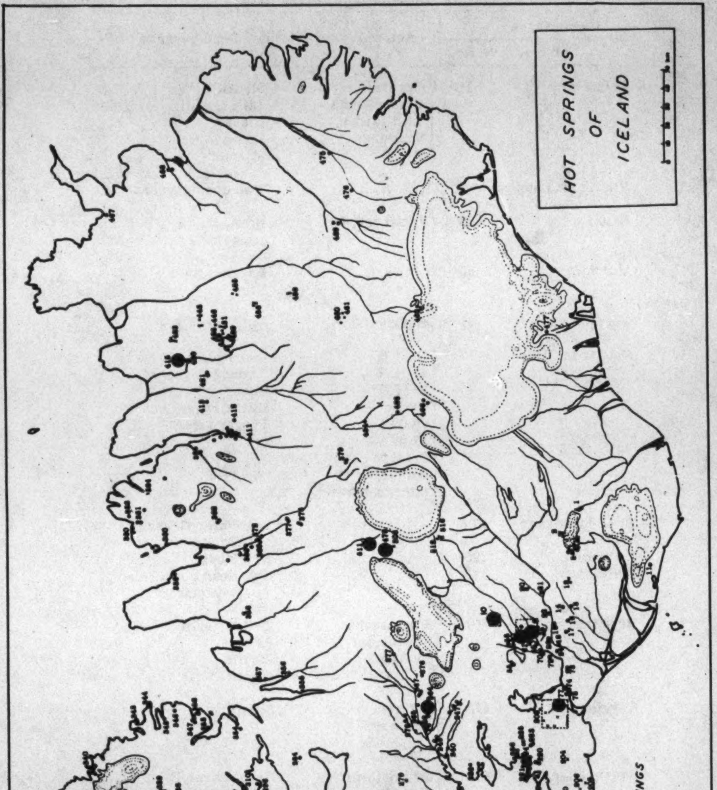
HOT SPRINGS OF ICELAND
REYKJAVIK
ALKALINE HOT SPRINGS
ACID HOT SPRINGS
GEYSER AREAS

Fig. 1--Map of Iceland showing the location of the hot springs and geysers

Among my own observations in this area I can mention Gosi which was a geyser with negligible discharge between eruptions. Every two hours it would throw a thin jet of water four m high.

The eruptions lasted for about ten minutes during which the water receded 60 cm down the pipe; then it slowly rose until the pipe was full and a new eruption started. The temperature was constantly 101°C both during the eruptions and during the quiet intervals.

In 1937 Gosi had ceased spouting and became an insignificant little spring, discharging only a small amount of hot water which just trickled among the gravel. However, just east of Gosi, within a distance of about three m, a new geyser had sprung up (called Gosi II in table).

Such observations indicate that within a few confined areas in Iceland the general conditions favoring geyser action have persisted for centuries, whereas such conditions are rarely present outside these areas. Nevertheless, some extinct geysers are known to have occurred outside the true geyser areas.

At Cape Reykjanes (no. 216), at an elevation of 21 m, a boiling spring is discharging almost pure sea water (salinity 47.9 per cent). In 1927 the spring was a true geyser with a regular period of 15 minutes, and the splashes were between three and six m high. In July 1928, the spring underwent a marked change. The period became irregular and on an average somewhat longer, that is, 20 to 25 minutes. The water jets also became lower. Eventually the geyser action ceased. It is now an incessantly boiling pot.

Kraflandi (no. 296) and two springs at Isafjardardjúp (no. 327) were famous geysers in the 19th century. It is remarkable that they occurred in Tertiary basalt, far removed from the zone of modern volcanism which is the home of all active geyser areas today.

BUNSEN [1847], investigated some of the geysers in Iceland in 1847, and came to the conclusion that there was a regular increase of the temperature from one eruption to another, and that this increase was effected by steam entering the well. The prerequisite for an eruption was that the boiling temperature would be closely approached at some depth in the well.

The results of my investigations in Iceland are at variance with Bunsen's conclusions: (1) There is no regular increase in the temperature from one eruption to another; each geyser shows a characteristic temperature-depth curve which does not change with time. (2) Although the temperature increases with depth, the increase is slower than that of the boiling point with depth. This means that the farther down the well, the farther away is the temperature from the boiling point at that depth.

These two statements are interrelated. If super-heat developed at greater depths, the ascending hot water would necessarily heat the upper part of the geyser system to temperatures far above those actually observed. This can be shown mathematically as follows.

A single vertical geyser pipe of uniform cross-section from top to bottom is assumed. Heat is transported upwards by the ascending mixture of water and gas bubbles. The temperature increases downward, because as the gas bubbles ascend, they expand and extract the latent heat of evaporation from the water. However, at a still greater depth, corresponding to the temperature T_1, the gas bubbles become vanishingly small. Below this level no further increase in temperature will take place (heat extracted by conduction through the rocks is negligible).

Let the discharge of water be c cm^3 per second per unit section (which is assumed to be the same through any section of the pipe). The volume of the spring gases is b cm^3 (reduced to 0°C normal pressure). In any one spring the ratio b/c is constant at any one time.

If there are no convection currents and no cooling at the surface, the measured temperature T, at a certain depth in the pipe where the hydrostatic pressure is P, has the following relation

$$P = p - p_0 + (b/c)[p \rho_0 r/(T_1 - T)] \qquad (1)$$

where p_0 is the atmospheric pressure, p the tension of the water vapor, ρ_0 is the density of the steam reduced to 0°C and normal pressure, and r is the latent heat of evaporation. This equation was deduced by THORKELSSON [1940].

This formula cannot be used on Great Geyser [BARTH, 1940] because the cooling is too strong at the surface. It has a large basin in which the water spreads out and cools to 75° C, giving rise to strong convection currents. Likewise the hot water does not enter at the bottom of the pipe, but at a depth of approximately 15 m, which complicates the water circulation.

In Uxahver and in Ystihver, the two most famous geysers in North Iceland, the characteristic temperature-depth curve was established down to six and eight m respectively by direct measurements. These geysers are built more simply and surface cooling plays a minor part. From the data obtained in them, it is easy to calculate that the temperature gradient at greater depths becomes very small. Indeed, the maximum temperatures, even at great depths, for Uxahver and Ystihver are only 108° C and 107° C, respectively (see Fig. 2), This reflects the fact already alluded to that at some depth there is no mechanism available for extracting heat from an ascending body of hot water. All temperture-depth profiles measured in bore holes of alkaline hot-spring regions in Iceland show the same (see Fig. 3), that is, practically no temperature gradient at depths below 20 to 30 m.

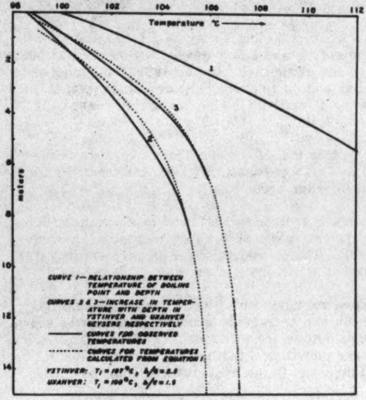

Fig. 2--Relation between temperature and depth in geyser wells

A bore hole in Yellowstone Park investigated by FENNER [1936] shows a totally different relation, for in the Yellowstone area the temperature-depth curve simply reflects the increase of the boiling point with depth.

Conclusions--The measurements from Iceland prove that geyser eruptions are not provoked by super-heat in the accessible parts of the geyser pipe. Calculations prove that in the deeper parts of the geyser system, which corresponds to the site of the development of the expulsive force, the temperature is far below the boiling point at that depth. It is concluded that geyser action is not caused by boiling or super-heating at any one point in the geyser system.

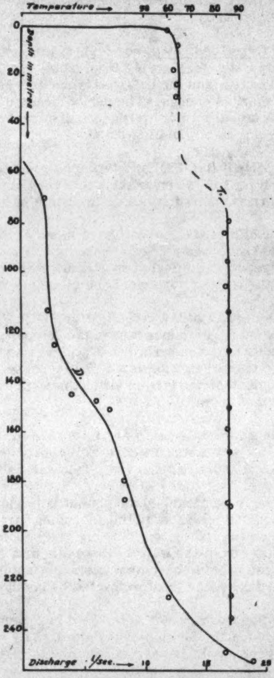

Fig. 3--Variation of temperature (T) and discharge (D) with depth, observed in a drill hole at Sudur Reykir, 1934

The theory of Th. Thorkelsson, which is supported by my observations and measurements, is that swarms of gas bubbles develop in the geyser pipe, forming a mixture of gas and water that has a hydrostatic pressure less than that of water alone, the result being a reduction of pressure which may produce an uprush of water sufficient to start the eruption.

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VALUE OF MIDWINTER SNOW SURVEYS

Wayne D. Criddle

Abstract--This paper discusses the forecasting of seasonal volume of runoff by means of snow surveys made earlier in the year than the first of April. Examples taken from the records of a few western streams illustrate the use of midwinter snow surveys in making forecasts. The relations used are compared with those based on April 1 snow surveys. A conclusion is that the forecast based on the maximum value of snow pack, whenever it occurs, may be superior to the forecast based on the value observed on the same date each year.

Since snow surveys were first begun there has been considerable question in the minds of the survey leaders and those dependent upon the results of the work regarding the proper time of year at which the snow surveys should be made to give the best possible indication of the following summer's runoff. Over much of the West it has been rather generally accepted that surveys made on April 1 of each year, when correlated with April to September runoff, usually give the best results. However, many of the snow-survey leaders believe that much value is being obtained from those surveys made on January 1, February 1, and March 1. This study attempts to determine the value of these early surveys and to show how they might be utilized along with the April 1 measurements.

In a paper by CRIDDLE and MARR [see "Reference" at end of paper, 1944], it was shown that ordinarily about 30 per cent of the total winter's snow cover falls in Columbia Basin during the month of January. As a result of the large snowfall which usually occurs during this period no attempt has been made here to show the relationship of the snow-water depth on the snow courses as of January 1 with the following summer's runoff. Only the snow-water depths as of the first of February, March, and April have been used.

Because of the extreme difficulty and expense in getting to the highest snow courses, it is quite common throughout the Columbia Basin for some of the lower and more accessible courses to be measured the first of each month throughout the winter and the higher and less accessible courses only on April 1. To a large extent April 1 water forecasts are based on the snow surveys at these higher altitudes. The early season measurements on the accessible courses have been used largely for information on the way in which the snow year was progressing and for the first indication of unusual developments in the water supply outlook. For some streams, the lower courses which are measured monthly throughout the winter may or may not be used in building up the actual forecast curve. This is especially true on the Boise River drainage where snow measurements have been made since 1930. The snow-water depth relationship to runoff for this river is based on data from three high snow courses, all of which are measured only on about April 1 of each year. The forecast curve based on these data has been exceedingly accurate to date. In only six of the past 16 years is the relationship in error more than ten per cent. In each of these six years, abnormal precipitation occurred in late spring and summer. On this Boise River drainage, three of the more accessible snow courses have been measured monthly since 1936. These courses are Bald Mountain at elevation 6260 feet, Cape Horn at elevation 6500 feet, and Redfish Lake at elevation 6600 feet. For purposes of this paper the average snow-water depth on these three courses for each year was computed for February 1, March 1, and April 1, and these averages plotted against the April 1 to September 30 runoff for each year (see Fig. 1). The best fitting curve was drawn through these points by eye. The data relating to the snow survey of February 1 are given in the first section of Table 1. These show that the per cent of error in estimating the six months' summer flow beginning April 1, averaged 14 per cent and varied from +28 to -42 per cent. For March, the average error was 20 per cent and varied from +47 to -34 per cent. Using the April snow surveys, the error averaged 17 per cent and varied from +49 to a -35 per cent. These data indicate that a forecast based on February 1 snow surveys would average three per-cent greater accuracy than those based on the April 1 surveys and would be six per cent more accurate than if based on the March 1 surveys. Likewise, the range in variation would be less. It should again be emphasized that these three courses are not at present the ones actually used in making streamflow forecasts on the Boise River. Only the April 1 surveys have been made regularly on the courses which are used.

Table 1--Data on snow surveys, forecasts, and actual runoff above division, from April 1 to September 30

Date of forecast	Snow-water depth on courses				Runoff			
	Bald Mountain	Cape Horn	Redfish Lake	Average	Forecast	Actual	Error	
	in	in	in	in	1000 ac ft	1000 ac ft	ac ft	pct
February 1								
1936	17.5	. . .	. . .	15.0[a]	1950	1666	+ 284	+ 17
1937	8.9	7.4	3.0	6.4	945	873	+ 72	+ 8
1938	. . .	10.2	5.4	8.6[a]	1200	2082	- 882	- 42
1939	. . .	5.4	5.1	5.8[a]	900	913	- 13	- 1
1940	5.0	17.1	2.9	8.3	1160	1150	+ 10	+ 1
1941	13.4	12.0	3.6	9.7	1300	1006	+ 294	+ 28
1942	13.0	11.2	4.3	9.5	1300	1234	+ 66	+ 5
1943	27.3	26.5	15.2	23.0	2840	2841	- 1	0
1944	3.8	6.4	2.0	4.1	700	898	- 198	- 22
March 1								
1936	25.6	. . .	. . .	20.6[a]	2270	1666	+ 603	+ 36
1937	16.7	14.0	6.2	12.9	1280	873	+ 407	+ 47
1938	16.5	16.2	8.5	13.7	1380	2082	- 702	- 34
1939	. . .	9.6	6.9	9.4[a]	810	913	- 103	- 11
1940	16.0	17.0	7.2	13.4	1340	1150	+ 190	+ 16
1941	16.2	12.0	5.3	11.2	1050	1006	+ 44	+ 4
1942	15.5	10.4	6.6	10.8	1000	1234	- 234	- 19
1943	28.8	29.6	16.2	24.7	2841	2841	0	0
1944	8.5	13.8	4.3	8.9	750	898	- 148	- 16
April 1								
1936	26.8	. . .	. . .	20.4[a]	2100	1666	+ 434	+ 26
1937	20.8	16.2	7.0	14.7	1300	873	+ 427	+ 49
1938	26.2	18.8	11.3	18.8	1880	2082	- 202	- 10
1939	17.6	9.0	6.2	10.9	800	913	- 113	- 12
1940	15.9	18.3	6.9	13.7	1180	1150	+ 30	+ 3
1941	15.1	13.2	4.6	11.0	800	1006	- 206	- 21
1942	14.3	11.6	7.0	11.0	800	1234	- 434	- 35
1943	33.6	27.3	15.8	25.6	2841	2841	0	0
1944	10.9	19.5	5.1	11.8	900	898	+ 2	0

[a] Partly estimated.

Another drainage area which was included in this study was that of the Clark Fork River in Montana. Average snow-water depths on eight relatively high courses were plotted against the six months' runoff, April to September, of Clark Fork River at Heron, Montana (see Fig. 2). Some of these courses are used in making the official water-supply forecast by the Soil Conservation Service. The average error in forecast for the period 1937-1944 (see Table 2) was 17 per cent when based on February 1 snow surveys, 16 per cent for March 1 surveys, and ten per cent for April 1 surveys. In other words, for this river, using the eight snow courses shown in the table, the forecast runoff on the average would be seven per cent more accurate when based on April 1 surveys than when based on February 1 surveys.

Snow surveys have been made on nine courses in the Upper Snake River Watershed in Wyoming since 1919. These surveys are made in the middle of each of the first four months of the year. The relationship of snow-water depth to runoff of the River for snow surveys of February 15, March 15, and April 15 are shown in Table 3 and Figure 3. The error in forecast runoff of the Snake River above Moran, Wyoming, shows an average of 12 per cent if based on the February 15 surveys with a range in error from a +36 to a -21 per cent. The average error in forecast, based on March 15 surveys, is 13 per cent, ranging from +26 to -35 per cent, and the average error based on the April 15 surveys is 17 per cent, ranging from +31 to -48 per cent. By using all of these courses with no other corrections, it is apparent that the more accurate forecast of the Snake River at Moran could be made by using the February 15 survey results.

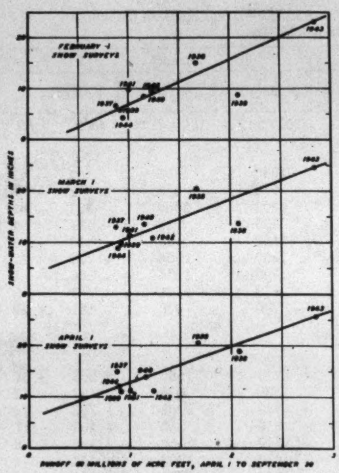

Fig. 1--Relationship of snow-survey data to volume of runoff, Boise River

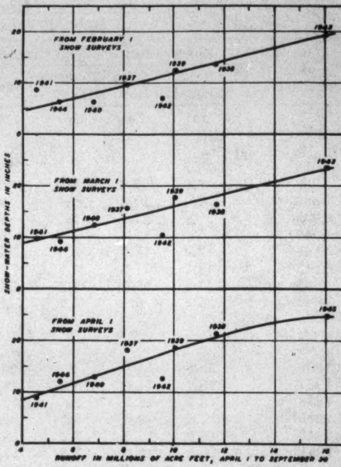

Fig. 2--Relationship of snow-survey data to volume of runoff, Clark Fork River

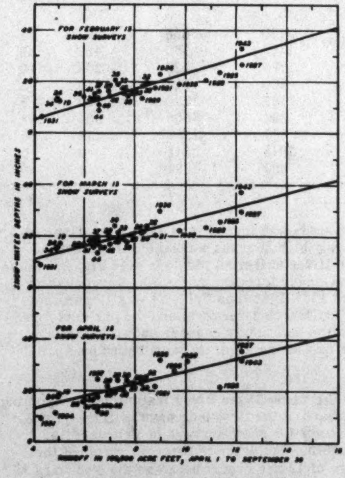

Fig. 3--Relationship of snow-survey data to volume of runoff, upper portion of Snake River

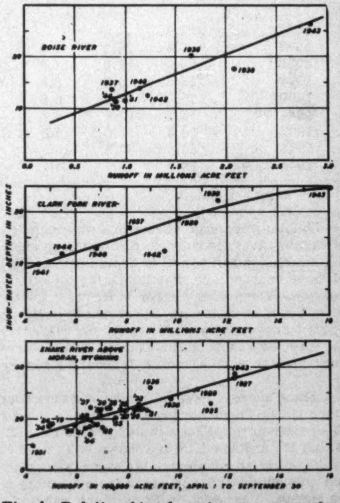

Fig. 4--Relationship of maximum snow-water depth data to volume of runoff

Table 2--Data on snow surveys, and forecast and actual runoff from April 1 to September 30, Clark Fork River

Date of forecast	Snow-water depth on courses									Runoff			
	Benton Spring	Chessman Reservoir	Gibbons Pass	Lookout Pass	Marias Pass	Nezperce Pass	Packers Meadow	Upper Ten-Mile Creek	Average	Forecast	Actual	Error	
	in	in	in	in	in	in	in	in	in	1000 ac ft	1000 ac ft	ac ft	pct
February 1													
1937	9.8	3.1	. . .	18.2	10.0	. . .	9.0	5.9	9.5[a]	8200	8135	+ 65	+ 1
1938	17.3	3.3	. . .	26.9	12.4	10.9	13.0	6.1	13.5[a]	11500	11680	- 180	- 2
1939	13.2	2.3	11.9	19.8	17.5	10.8	13.4	9.0	12.2	10400	10103	+ 397	+ 4
1940	7.8	1.6	7.8	11.1	3.4	6.2	6.7	4.7	6.2	5500	6828	- 1328	- 20
1941	12.7	2.1	10.6	15.9	7.4	4.9	9.7	4.8	8.5	7600	4554	+ 3046	+ 67
1942	5.2	2.8	13.4	10.9	4.6	6.0	3.8	8.8	6.9	6000	9584	- 3584	- 37
1943	19.8	5.8	23.4	29.3	15.4	19.8	27.0	13.5	19.2	16000	16126	- 126	- 1
1944	8.7	0.8	5.7	12.4	4.6	5.9	6.4	4.2	6.1	5400	5454	- 54	- 1
March 1													
1937	17.7	5.7	15.3	30.4	16.0	11.8	16.9	10.4	15.5	9800	8135	+ 1665	+ 20
1938	23.3	3.9	16.8	33.9	15.6	11.2	17.5	7.6	16.2	10400	11680	- 1280	- 11
1939	18.5	4.9	17.5	28.2	21.8	15.6	22.1	12.8	17.7	11400	10103	+ 1297	+ 13
1940	14.2	3.3	14.4	20.9	9.7	11.7	15.4	8.0	12.2	7000	6828	+ 1172	+ 17
1941	12.6	1.7	13.8	18.6	7.3	6.6	10.1	5.8	9.6	4700	4554	+ 146	+ 3
1942	8.8	4.2	18.0	14.9	6.7	9.2	8.6	11.9	10.3	5800	9584	- 3784	- 40
1943	21.3	7.4	30.6	36.3	19.4	27.2	28.1	15.0	23.2	16000	16126	- 126	- 1
1944	10.8	1.9	10.2	16.2	7.2	8.7	10.0	6.9	9.0	4200	5454	- 1254	- 23
April 1													
1937	19.0	6.9	. . .	32.8	16.8	13.6	18.2	13.3	18.0[a]	10000	8135	+ 1865	+ 23
1938	28.3	5.9	. . .	40.1	18.6	15.4	21.1	11.4	21.1[a]	12200	11680	+ 520	+ 4
1939	18.9	3.2	20.5	31.0	20.4	17.2	23.3	12.7	18.4	10200	10103	+ 97	+ 1
1940	14.2	1.9	16.9	20.8	10.1	13.0	15.5	10.2	12.8	6800	6828	- 28	0
1941	10.0	0.9	14.3	17.1	5.6	6.2	8.4	6.4	8.6	4200	4554	- 354	- 8
1942	10.1	4.4	21.6	18.9	9.7	11.1	11.0	13.0	12.5	6600	9584	- 2984	- 31
1943	22.0	7.2	28.8	38.2	22.2	26.7	31.6	18.1	24.4	16000	16126	- 126	- 1
1944	10.3	3.6	14.9	18.2	9.4	13.9	13.8	10.5	11.8	6100	5454	+ 646	+ 12

[a] Partly estimated.

Table 3--Data on snow surveys, and forecast and actual runoff from April 1 to September 30, Snake River above Moran, Wyoming

Date of forecast	Snow-water depths on courses										Runoff			
	Arizona	Astor Creek	Coulter Creek	Glade Creek	Huckleberry Divide	Lewis Lake Div.	Moran	Moran Bay	Snake River, Sta.	Average	Forecast	Actual	Error	
	in	in	in	in	in	in	in	in	in	in	1000 ac ft	1000 ac ft	ac ft	pct
February 15														
1919	9.0	13.5	12.0	13.5	12.5	18.0	6.5	11.5	12.0	12.1	590	503	+ 87	+ 17
1920	11.0	17.0	13.0	13.5	13.0	24.0	8.0	12.5	12.5	13.8	685	827	- 142	- 17
1921	15.5	22.5	17.5	21.5	17.0	27.0	11.0	15.0	14.0	17.9	815	880	- 65	- 7
1922	15.0	21.0	15.5	19.0	17.0	31.5	11.5	17.0	16.0	18.2	825	833	- 8	- 1
1923	11.5	17.0	14.0	16.0	14.0	28.5	10.0	14.5	14.5	15.6	740	791	- 51	- 6
1924	9.0	14.0	15.0	15.0	13.0	22.0	7.0	14.0	13.0	13.6	675	496	+ 179	+ 36
1925	17.0	33.0	22.0	25.0	20.0	46.0	11.5	21.0	20.0	23.9	1010	1135	- 125	- 11
1926	10.5	13.5	13.5	12.5	11.0	32.0	8.0	13.0	12.0	14.0	690	597	+ 93	+ 16
1927	20.0	37.0	25.0	26.0	21.0	60.0	11.0	21.0	23.0	27.1	1120	1221	- 101	- 8
1928	12.5	30.0	22.5	21.0	14.5	43.0	8.0	14.5	17.5	20.4	900	1061	- 181	- 17
1929	12.0	22.0	15.0	18.0	14.0	26.0	10.0	16.0	15.0	16.4	765	694	+ 71	+ 10
1930	10.5	18.0	11.5	14.0	11.0	27.0	6.5	12.5	11.0	13.6	675	656	+ 19	+ 3
1931	5.5	8.0	6.0	6.5	6.0	8.5	4.0	6.5	5.0	6.2	430	429	+ 1	0
1932	17.0	25.0	20.0	19.0	18.5	33.5	10.5	18.5	17.0	19.9	880	844	+ 36	+ 4
1933	14.5	25.5	19.0	19.5	16.0	34.0	11.0	15.0	16.0	18.8	845	733	+ 112	+ 15
1934	11.5	17.0	15.0	12.5	11.0	22.5	6.0	9.0	12.0	12.9	650	490	+ 160	+ 33
1935	10.5	18.5	16.0	14.0	13.5	24.5	8.0	10.5	13.5	14.3	700	772	- 72	- 9
1936	18.7	29.5	21.0	23.0	19.7	38.5	14.2	22.5	21.0	23.1	988	898	+ 90	+ 10
1937	13.8	19.9	16.8	18.0	14.9	25.0	7.5	15.3	14.3	16.2	760	654	+ 106	+ 16
1938	14.8	25.9	18.5	19.6	16.7	35.4	8.0	15.6	15.5	18.9	850	975	- 125	- 13
1939	15.0	24.2	20.6	21.8	17.1	35.1	10.5	18.5	20.9	20.4	897	721	+ 176	+ 24
1940	9.0	11.3	11.3	11.8	9.9	16.4	8.1	12.3	11.3	11.3	600	655	- 55	- 8
1941	13.6	17.5	13.8	16.8	14.1	26.8	7.4	15.3	12.5	15.3	730	639	+ 91	+ 14
1942	12.2	18.0	11.8	13.8	13.4	25.4	8.4	14.4	12.8	14.5	703	701	+ 2	0
1943	25.5	46.4	33.7	31.8	27.3	55.4	17.3	33.1	28.8	33.3	1320	1223	+ 97	+ 8
1944	6.5	11.6	9.6	8.4	8.1	16.2	4.0	8.6	7.9	9.0	520	655	- 135	- 21
1945	12.5	16.4	16.4	16.6	13.7	26.0	9.2	12.3	15.2	15.4	734	756	- 22	- 3
March 15														
1919	13.0	16.5	16.5	17.0	13.5	36.0	8.5	15.5	15.0	16.8	620	503	+ 177	+ 23
1920	16.5	26.5	23.0	24.0	18.0	37.5	12.0	18.5	17.5	21.5	805	827	- 22	- 3
1921	16.0	17.0	20.5	23.5	17.5	36.0	11.0	17.0	17.0	20.6	770	880	- 110	- 13
1922	18.0	28.0	21.5	23.5	20.0	36.0	11.5	18.0	21.5	22.0	825	833	- 8	- 1
1923	16.0	26.0	20.0	21.5	19.5	35.0	14.0	15.5	19.0	20.7	770	791	- 71	- 10
1924	10.0	21.0	15.5	18.0	13.5	26.5	8.0	15.0	15.0	15.8	580	496	+ 84	+ 17
1925	19.0	35.0	23.5	27.0	22.0	48.5	13.5	23.0	22.0	25.9	980	1135	- 155	- 14
1926	12.5	16.5	17.0	16.0	13.0	35.0	8.5	15.5	15.0	16.6	610	597	+ 13	+ 2
1927	24.0	45.0	28.0	32.0	26.0	42.0	15.0	27.0	28.0	29.7	1120	1221	- 101	- 8
1928	18.0	33.5	23.5	22.0	20.0	47.0	10.0	19.5	20.5	23.8	895	1081	- 186	- 17

1929	15.0	27.0	20.0	22.0	18.0	33.0	11.5	18.0	17.5	20.2	620	694	+ 61	+ 9
1930	12.5	22.0	16.0	16.0	14.0	32.0	8.5	15.0	15.0	16.8	775	656	- 36	- 5
1931	6.5	12.0	8.0	8.5	8.0	13.0	5.0	7.5	7.0	8.4	280	429	- 149	- 35
1932	20.5	30.0	23.0	24.0	22.0	42.0	12.5	21.0	21.0	24.0	900	844	+ 56	+ 7
1933	17.0	29.5	21.5	22.0	18.5	36.0	12.5	17.0	20.5	21.6	810	733	+ 77	+ 10
1934	14.0	20.0	17.0	14.5	13.5	26.0	7.0	12.0	13.5	15.3	560	490	+ 70	+ 14
1935	14.0	23.0	17.5	18.0	16.0	33.0	9.5	15.0	15.5	17.9	665	772	- 107	- 14
1936	24.4	37.0	27.5	32.0	25.0	51.0	16.5	30.0	25.9	29.9	1135	898	+ 237	+ 26
1937	15.5	23.5	19.9	21.8	16.4	33.5	9.0	21.0	17.0	19.7	735	654	+ 81	+ 12
1938	18.2	29.5	22.0	23.4	19.8	40.5	10.4	21.0	18.1	22.5	845	975	- 130	- 13
1939	19.2	28.0	22.9	25.2	20.2	44.2	11.3	22.7	22.5	24.0	900	721	+ 179	+ 25
1940	15.0	19.6	17.6	21.4	15.7	30.1	11.2	19.5	16.4	18.5	685	655	+ 30	+ 4
1941	13.0	16.1	14.8	16.4	13.3	28.5	9.7	16.0	14.1	15.8	580	639	- 59	- 9
1942	13.1	21.1	14.6	16.2	14.5	28.6	9.3	18.1	14.2	16.6	610	701	- 91	- 13
1943	31.8	50.5	36.4	36.0	31.5	62.6	20.1	35.7	32.6	37.5	1435	1223	+ 212	+ 17
1944	10.4	18.3	13.8	13.4	12.4	24.4	6.6	11.2	11.1	13.5	490	655	- 165	- 25
1945	15.0	19.2	20.9	18.0	16.8	29.9	11.1	19.4	18.1	18.7	695	756	- 61	- 8
April 15														
1919	13.0	21.5	18.0	19.0	15.0	37.0	10.0	17.0	15.0	18.4	620	503	+ 117	+ 23
1920	18.5	25.0	22.5	24.5	21.5	39.0	13.5	20.5	21.5	22.9	795	827	- 32	- 4
1921	13.0	31.5	22.0	28.0	18.5	49.0	6.4	13.0	15.5	21.9	755	880	- 125	- 14
1922	15.5	30.0	22.0	30.5	19.5	42.0	12.0	19.0	20.0	23.4	820	833	- 13	- 2
1923	18.0	28.0	21.0	24.0	20.0	43.0	14.5	18.5	20.0	23.0	800	791	+ 9	+ 1
1924	10.0	22.0	17.0	19.0	16.0	32.0	10.0	16.5	17.0	17.7	585	496	+ 89	+ 18
1925	13.0	30.0	18.0	27.0	19.0	47.5	7.0	19.0	16.5	21.9	755	1135	- 380	- 33
1926	9.0	18.0	14.0	15.0	13.0	38.0	4.5	17.0	12.0	15.6	500	597	- 97	- 16
1927	25.0	49.0	32.0	36.0	28.0	76.0	16.0	31.0	30.0	35.9	1325	1221	+ 104	+ 9
1928	21.5	46.5	28.0	34.0	23.5	60.0	15.0	27.0	28.0	31.5	1145	1081	+ 64	+ 6
1929	17.0	27.0	20.0	24.0	19.0	36.0	12.5	20.0	19.5	21.7	745	694	+ 51	+ 7
1930	8.0	22.5	11.0	10.0	10.0	24.0	0.0	10.5	9.0	11.7	340	656	- 316	- 48
1931	6.0	17.5	8.0	9.0	8.0	17.0	0.0	8.0	7.0	8.9	230	429	- 199	- 46
1932	19.0	33.0	26.0	25.0	25.0	45.0	10.0	20.0	22.0	25.0	880	844	+ 36	+ 4
1933	18.0	34.5	24.5	22.5	19.5	41.5	13.0	20.0	22.5	24.0	840	733	+ 107	+ 15
1934	11.5	24.0	20.0	16.5	12.0	35.5	0.0	10.0	12.0	15.7	500	490	+ 10	+ 2
1935	18.5	35.0	23.5	23.0	20.0	44.0	10.0	19.5	20.5	23.8	835	772	+ 63	+ 8
1936	25.5	40.0	28.0	32.0	27.0	55.0	16.0	37.5	27.0	32.0	1165	898	+ 267	+ 30
1937	20.0	30.0	23.5	23.8	21.2	43.0	10.5	25.5	21.5	24.3	855	654	+ 201	+ 31
1938	22.6	37.6	27.6	27.1	25.0	52.5	9.0	25.0	22.5	27.1	990	975	+ 15	+ 2
1939	15.4	22.2	15.8	20.0	17.5	36.5	6.3	20.7	17.2	19.1	640	721	- 81	- 11
1940	10.9	18.2	15.7	21.0	16.1	37.2	3.5	21.7	14.2	17.6	580	655	+ 75	+ 11
1941	11.0	18.6	15.7	15.3	12.8	27.6	0.0	10.0	9.3	13.4	410	639	- 229	- 36
1942	10.9	19.1	13.0	12.6	13.8	28.5	5.1	16.3	7.2	14.1	440	701	- 261	- 37
1943	23.7	50.8	28.0	34.9	29.3	62.5	8.5	25.0	25.2	32.0	1165	1223	- 58	- 3
1944	9.8	20.1	13.2	13.4	13.0	25.6	5.1	11.0	11.6	13.6	420	655	- 235	- 36
1945	15.0	21.9	23.6	19.9	18.1	33.2	11.0	20.8	18.9	20.3	695	756	- 61	- 8

Table 4--Data on maximum snow-water depth, and forecast and actual runoff from April 1 to September 30, Boise River

Year	Snow-water depth on courses[a]				Runoff			
	Bald Mountain	Cape Horn	Redfish Lake	Average	Forecast	Actual	Error	
	in	in	in	in	1000 ac ft	1000 ac ft	ac ft	pct
1936	26.8	. . .		20.4[b]	2030	1666	+ 364	+ 22
1937	20.8	16.2	7.0	13.7	1140	873	+ 267	+ 31
1938	26.2	18.8	11.3	18.8	1820	2082	- 262	- 13
1939	17.6	9.6[c]	6.9[c]	11.4	850	913	- 63	- 7
1940	16.0[c]	18.3	7.2	13.8	1150	1150	0	0
1941	16.2[c]	13.2	5.3	11.6	860	1006	- 146	- 15
1942	15.5[c]	11.6	7.0	11.4	850	1234	- 384	- 31
1943	33.6	29.6[c]	16.2[c]	26.5	2840	2841	- 1	0
1944	10.9	19.5	5.1	11.8	900	898	+ 2	0

[a] All snow-water measurements were made April 1 unless otherwise noted.
[b] Partly estimated.
[c] March 1 measurement.

These data show that for the Boise River, if the only snow surveys available were for the three courses herein studied, the runoff of this river could be more accurately forecast from the February 1 snow surveys than from the March or April surveys. The snow-survey stations used in estimating runoff of the Clark Fork River at Heron, Montana, are part of those actually used in our official forecasting work. Some of the stations used in the official forecast are not measured monthly, and therefore cannot be included in this study. However, for this river it appears that seven per cent more accuracy may be expected when the April 1 surveys are used in preference to the February 1 surveys. The snow courses on the upper Snake River are those upon which the official runoff forecast has largely been based. This study indicates that the runoff could be more accurately forecast by using the February 15 surveys than by using individually either the March or April surveys.

Actually it has been the policy of those responsible for making the streamflow forecasts in Columbia Basin to use, frequently, the greatest snow depth that is measured whether it be on the April 1 survey or the February or March survey. To illustrate this point, forecast curves for each of the three watersheds studied were prepared (see Fig. 4), using the maximum snow-water depth measured on each course regardless of the month, and a probable forecast of runoff made. From Table 4 it will be seen that for three of the nine years studied on the Boise River, the Bald Mountain snow course had the greatest snow pack on March 1. Cape Horn and Redfish Lake snow courses each had greater depths of snow water on March 1 for two of the nine years.

The data for Clark Fork in Table 5 similarly shows that the greatest snow depth occurred 14 times in 64 on the first of March and three times on the first of February. The data for Snake River above Moran, Wyoming in Table 6 shows that the maximum snow-water depth occurred 159 times in 243 in the middle of April, 81 times in the middle of March, and three times in the middle of February. It is important to note that the accuracy of the forecast for each river when based on the maximum snow-water depth was greater than when based on any one month's measurements alone (see Table 7).

Summary and conclusions of this study--The following points are drawn from this study: (1) Experience has shown that greater accuracy of forecast may be generally expected by using the maximum snow-water depth for each course regardless of the month this maximum depth occurs. However, this may not always hold if an entire watershed is at low elevation and subject to intermittent winter melting. (2) For maximum accuracy in streamflow forecasting, snow surveys should be made, at least on certain key courses, the first of February and especially the first of March as well as regularly on April 1. (3) If no other courses were measured than those studied in this report, greater accuracy could generally be obtained in forecasting the Boise River by using the February 1 snow surveys than for any other month; Clark Fork by using the April 1 surveys; and the upper Snake River by using February 15 surveys. (4) Even the highest existing snow courses may have greater snow packs on February 1 or March 1 than on April 1 of some years. (5) The data in this paper indicate the value of early snow measurements in forecasting runoff. Past experience has shown the value of an April 1 forecast of the summer runoff, but of even greater

Table 5--Data on maximum snow-water depth, and forecast and actual runoff from April 1 to September 30, Clark Fork River

Year	Snow-water depths on courses[a]									Runoff			
	Benton Spring	Chessman Reservoir	Gibbons Pass	Lookout Pass	Marias Pass	Nezperce Pass	Packers Meadow	Upper Ten-Mile Creek	Average	Forecast	Actual	Error	
	in	in	in	in	in	in	in	in	in	1000 ac ft	1000 ac ft	ac ft	pct
1937	19.0	6.9	15.3[b]	32.8	16.8	13.6	18.2	13.3	17.0	8950	8135	+ 815	+ 10
1938	28.3	5.9	16.8[b]	40.1	18.6	15.4	21.1	11.4	22.2	12700	11680	+ 1020	+ 9
1939	18.9	4.9[b]	20.5	31.0	21.8[b]	17.2	23.3	12.8[b]	18.8	10000	10103	- 3	0
1940	14.2	3.3[b]	16.9	20.9[b]	10.1	13.0	15.5	10.2	13.0	6450	6828	- 378	- 6
1941	12.7[c]	2.1[c]	14.3	18.6[b]	7.4[c]	6.6[b]	10.1[b]	6.4	9.8	4500	4554	- 54	- 1
1942	10.1	4.4	21.6	18.9	9.7	11.1	11.0	13.0	12.5	6200	9584	- 3384	- 35
1943	22.0	7.4[b]	30.6[b]	38.2	22.2	27.2[b]	31.6	18.1	24.7	16100	16126	- 26	0
1944	10.8[b]	3.6	14.9	18.2	9.4	13.9	13.8	10.5	11.9	5800	5454	+ 346	+ 6

[a] All snow-water measurements were made on April 1 unless otherwise noted.

[b] March 1 measurement.

[c] February 1 measurement.

Table 6--Data on maximum snow-water depth, and forecast and actual runoff from April 1 to September 1, Snake River above Moran, Wyoming

Year	Snow-water depths on courses[a]										Runoff			
	Arizona	Aster Creek	Coulter Creek	Glade Creek	Huckleberry Divide	Lewis Lake Divide	Moran	Moran Bay	Snake River Station	Average	Probable forecast	Actual	Error	
	in	in	in	in	in	in	in	in	in	in	1000 ac ft	1000 ac ft	ac ft	pct
1919	13.0	21.5	18.0	19.0	15.0	37.0	10.0	17.0	15.0	18.4	610	503	+ 107	+ 21
1920	18.5	26.0[c]	23.0[c]	24.5	21.5	39.0	13.5	20.5	21.5	23.1	775	827	- 52	- 6
1921	16.0[c]	31.5	22.0	28.0	18.5	49.0	11.0[c]	17.0[c]	17.0[c]	23.3	785	880	- 95	- 11
1922	18.0[c]	30.0	22.0	30.5	20.0[c]	42.0	12.0	19.0	21.5[c]	23.9	805	833	- 28	- 3
1923	18.0	28.0	21.0	24.0	20.0	43.0	14.5	18.5	20.0	23.0	773	791	- 18	- 2
1924	10.0	22.0	17.0	19.0	16.0	32.0	10.0	16.5	17.0	17.7	585	496	+ 89	+ 18
1925	19.0[c]	35.0[c]	23.5[c]	27.0	22.0[c]	48.5[c]	13.5[c]	23.0[c]	22.0[c]	25.9	875	1135	- 260	- 23
1926	12.5[c]	18.0	17.0	16.0[c]	13.0	38.0	8.5[c]	17.0	15.0[c]	17.2	570	597	- 27	- 5
1927	25.0	49.0	32.0	36.0	28.0	76.0	16.0	31.0	30.0	35.9	1225	1221	+ 4	0
1928	21.5	46.5	28.0	34.0	23.5	60.0	15.0	27.0	28.0	31.5	1070	1081	- 11	- 1
1929	17.0	27.0	20.0	24.0	19.0	36.0	12.5	20.0	19.5	21.7	725	694	+ 31	+ 4
1930	12.5[c]	22.5	16.0[c]	16.0[c]	14.0[c]	32.0[c]	8.5[c]	15.0[c]	15.0[c]	16.8	555	656	- 101	- 15
1931	6.5[c]	17.5	8.0	9.0	8.0	17.0	5.0[c]	8.0	7.0	9.6	300	429	- 129	- 30
1932	20.5[c]	33.0	26.0	25.0	25.0	45.0	12.5[c]	21.0[c]	22.0	25.6	864	844	+ 20	+ 2
1933	18.0	34.5	24.5	22.5	19.5	41.5	13.0	20.0	22.5	24.0	808	733	+ 75	+ 10
1934	14.0[c]	24.0	20.0	16.5	13.5[c]	35.5	7.0[c]	12.0[c]	13.5[c]	17.3	570	490	+ 80	+ 16
1935	18.5	35.0	23.5	23.0	20.0	44.0	10.0	19.5	20.5	23.8	800	772	+ 28	+ 4
1936	25.5	40.0	28.0	32.0	27.0	55.0	16.5[c]	37.5	27.0	32.1	1092	898	+ 194	+ 22
1937	20.0	30.0	23.5	23.8	21.2	43.0	10.5	25.5	21.5	24.3	820	654	+ 166	+ 25
1938	22.6	37.6	27.6	27.1	25.0	52.5	10.4[c]	25.0	22.5	27.8	945	975	- 30	- 3
1939	19.2[c]	28.0[c]	22.9[c]	25.2[c]	20.2[c]	44.2[c]	11.3[c]	22.7[c]	22.5[c]	24.0	808	721	+ 87	+ 12
1940	15.0[c]	19.6[c]	17.6[c]	21.4[c]	16.1	37.2	11.2[c]	21.7	16.4[c]	19.6	653	655	- 2	0
1941	13.6[b]	18.6	15.7	16.8[b]	14.1[b]	28.5[c]	9.7[c]	16.0[c]	14.1[c]	16.3	536	639	- 103	- 16
1942	13.1[c]	21.1	14.6[c]	16.2[c]	14.5[c]	28.6[c]	9.3[c]	18.1[c]	14.2[c]	16.6	547	701	- 154	- 22
1943	31.8[c]	50.8	36.4[e]	36.0[c]	31.5[c]	62.6[c]	20.1[c]	35.7[c]	32.6[c]	37.5	1283	1223	+ 60	+ 5
1944	10.4[c]	20.1	13.8[c]	13.4	13.0	25.6	6.6[c]	11.2[c]	11.6	14.0	455	655	- 200	- 30
1945	15.0	21.9	23.6	19.9	18.1	33.2	11.1[c]	20.8	18.9	20.3	680	756	- 76	- 10

[a] All snow-water depths are for April 15 unless otherwise noted.

[b] February 15 measurement.

[c] March 15 measurement.

Table 7--Comparison of accuracy in forecasting streamflow based on surveys made at various times

Snow-survey data	Error in April 1 to September 30 streamflow forecast		
	Average error	Range of error	
		Plus	Minus
	pct	pct	pct
Boise River			
February 1	14	28	42
March 1	20	47	34
April 1	17	49	35
Maximum depth	13	31	31
Clark Fork River			
February 1	17	67	37
March 1	16	20	40
April 1	10	23	31
Maximum depth	8	10	35
Upper Snake River			
February 15	12	36	21
March 15	13	26	35
April 15	17	31	48
Maximum depth	12	30	25

value, because of the time element, would be a preliminary forecast on March 1 or February 1 even though the forecast may not be quite so accurate. Later surveys may be utilized to refine the early forecasts.

Reference

CRIDDLE, WAYNE D., and MARR, JAMES C., Midwinter forecasting of the snow-water runoff on years of extremely light or heavy February 1 mountain snow-covers, Trans. Amer. Geophys. Union, pt. 1, pp. 141-148 1944.

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DISCUSSION

R. A. Work (Soil Conservation Service, Medford, Oregon)--In connection with the value of these early season snow surveys, in some areas of the West, the planting plans of farmers and other water users must be complete and put into effect prior to April 1, and a forecast issued following April 1 is of little value to individuals who have already seeded their land or decided not to seed their land.

Another point, with a correct regulation of western water supplies there have come into being a very large number of reservoirs. Those people charged with the responsibility of regulating those reservoirs for irrigation or flood control are finding increasing use for snow surveys made periodically through the winter months. In other words, they cannot wait until April 1 to regulate reservoirs, but they have to keep on hand a constant ledger of their water resources--the inflow that may be expected, and the demands upon the reservoir. I therefore agree with Criddle in his ambition to refine the snow-survey work to the point at which it will be of maximum use to the greatest number of water users.

L. Standish Hall (East Bay Municipal Utility District, Oakland, California)--I find I have to take the snow survey data in California and set up an estimate of what the probable runoff will be, making allowance for the normal precipitation in the fall months. I think the February 1 forecast, though it is rather sketchy, can be used to get a relation for key stations and main stations, by which I am able to make an estimate that is at least a guide. If we have a wet March and April, the forecast may be increased materially, but at least one has a fairly good estimate put together in February.

There is another angle to the snow-survey forecast that relates to the time the snow melts. Frequently the resuls, as far as irrigation and water supply are concerned, are greatly affected by the matter of when the snow melts. For example, say on the Mokelumne River, the normal snow runoff is 500,000 ac ft, but in April there is very little runoff, say 100,000 ac ft. That leaves 400,000 ac ft. In May the runoff may be only 150,000 ac ft; then there are 250,000 ac ft left that will run off in June and July. One then has good information on the late runoff. However, if the season is reversed and there are early April and May meltings, even though the February forecast was normally ten per cent accurate, it may be difficult to know with any degree of accuracy how much snow water will be available for late season runoff. Again assuming a normal snow runoff of 500,000 ac ft, if 450,000 ac ft runs off during April and May we would expect 50,000 ac ft still to come down. However, taking into account the possible error of forecast there may be as much as 100,000 ac ft yet to come or there may be practically none left. That points out one of the difficulties in applying some of these forecasts to actual operations.

G. E. Carroll (U. S. Engineer Office, Los Angles, California)--One of the problems that is being studied in the Planning Branch is the operation of reservoirs for flood control. The biggest problem concerns the peak years of snow melt. Many peak floods could be controlled if it were forecast on February 1 or March 1, that it was going to be a high-runoff year. With that knowledge, reservoirs in the southern San Joaquin and on the Truckee Rivers could be pulled down in time. Without such knowledge, that cannot be done, as to release the water to small individual reservoirs, takes in many cases 60 days or so. Many of our operations now contemplate having such snow-survey information available as a preliminary forecast the first of February.

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SEASONAL STORAGE PRECIPITATION GAGES

Ashton R. Codd

Abstract--This paper describes briefly, a non-recording winter storage precipitation gage used successfully in the regions of heavy snowfall in the Sierras of California.

Because of the many inquiries received in the Office of the United States Weather Bureau in Sacramento, California, regarding the latest developments and design of seasonal storage precipitation gages now in operation throughout the Sierras, the following descriptive report is presented.

The need for a type of precipitation gage that can be set out in an isolated location, unattended for months at a time and thereby obtain a record of precipitation during the unattended period, has been the inspiration for this development work during the past eight years. At the present time we are using a gage which appears to meet these specifications with some limitations. The present type of gage can be placed at a remote station in the mountains, and when prepared for operation in the fall will continue on through the winter until it is visited and measured. The storage gage is not a recording gage as it will not give a record of the daily catch. The total catch between visits is the only figure obtainable. These visits can be as often as the particular need for them justifies the expense of sending a man to the gage on skis, snowshoes or other means of transportation. The principal function of the gage is to sample the storms as they pass and give a precipitation record by the storm, monthly or seasonal, as attendance is available.

Let us take a typical example of some location at which this type of gage has been installed to demonstrate their usefulness and how the gage is managed to obtain the required information. In the headwaters of the North Fork of the San Joaquin River there are no annual precipitation records, or we should say no precipitation records during the period when 90 per cent of the annual precipitation falls. The little town of North Fork at an elevation of 2,665 feet is the highest existing station now in operation.

There is a very large water-contributing area between this elevation and 13,000 feet, the top of the range. In this large area is located a United States Forest Service Ranger Station at Clover Meadow, which is occupied from about the first of June through October. With the cooperation of the Sierra National Forest Supervisor and the district ranger, a seasonal storage precipitation gage was erected on November 3, 1945. The gage was placed in operation and the initial readings taken on that date. Visits were made during the spring and the seasonal total was read when the ranger station was opened for the summer. The ranger then set up his manual gage to keep the summer record as before. This total annual record is a new feature of this station. In the fall the ranger again charges the storage gage and starts it for the winter season. With reasonable care and an understanding of the principle of the storage gage, a good record will be made available where none existed before.

The gage is constructed large enough to hold a sufficient quantity of calcium chloride solution (34 per cent by weight), so that when the season's precipitation is added, the resulting solution will not freeze. The solution is covered with a film of light oil to prevent evaporation. The initial charge is weighed and checked for volume by depth measurement. Occasional measurements are made by depth and the seasonal volume is determined by weighing and checking the depth of solution. The difference in weights is the most accurate and dependable measurement. The required quantity of initial charge is estimated to be equal to about one and one-half times the estimated average annual precipitation for the particular site under consideration. Where the estimated average annual precipitation is 40 inches, and equivalent of 60 inches of calcium chloride solution is used. The amount of oil used should be sufficient to cover the solution about one-sixteenth of an inch thick. This amount is usually equivalent to one-half inch of precipitation.

The gage is constructed in a conical shape with the standard eight-inch orifice. The sidewalls of the gage slope at approximately six vertical to one horizontal. Satisfactory gages have been built having a capacity of 60, 100, 200, and 300 inches of precipitation. A reasonable free-board above the solution is necessary and must be anticipated in selecting the size of the gage to be used, especially where large volumes of snow are expected during a short period of time. Where 40 inches of precipitation are expected, the 200-inch gage is installed so that there will be sufficient freeboard above the solution when the resulting 100 inches of dilute liquid is contained in the gage. The gage is supported on a steel tower. The orifice of the gage is surrounded by an Alter shield to insure a consistent catch during storms accompanied by wind. The height of the tower is chosen to insure that the gage will stand clear of the deepest anticipated depth of snow. Consequently, the tower is built in five-foot sections so that an alteration can be made without undue expense and also to facilitate transportation.

At the present time the instrumental cost of a single installation is approximately $200. This includes a 200-inch gage, a 15-foot tower complete with shield. The gage itself costs approximately $40. The tower sections cost approximately $45.per five-foot section, including one shield, shield supports, and gage supports.

In the past, these instruments have been built by contract with steel construction companies, under the supervision of the Office of the United States Weather Bureau in Sacramento, California. To our knowledge, there is no manufacturer who carries them in stock. Plans and specifications are available to those agencies or companies who desire to embark on their own construction program. The annual cost of calcium chloride and oil is approximately two dollars. No doubt the question will arise as to the low cost of the gage and the high cost of the tower. This is one of the unfortunate features of designing a tower to withstand snow and wind loads that will be rigid enough to carry a large recording gage, should such be desired.

From time to time, several agencies have cooperated with the United States Weather Bureau in building gages. The Bureau has directed the construction, installation, and instruction of observers. This procedure is highly desirable because the observer is started on a standard practice through which it is believed good results are obtained. When the method of operation is understood and the correct details followed, the storage precipitation gage becomes a very simple and efficient instrument.

These gages and towers have been tested for several years at Soda Springs, California, with satisfactory results. In the summer and fall of 1945, eight gages were installed at isolated locations in the Sierras, where they will partially fill the need for additional precipitation records at high elevations.

U. S. Weather Bureau,
Sacramento, California

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LOW-COST STORAGE-TYPE PRECIPITATION GAGES

Herman J. Fittinger

Abstract--A non-recording, large-capacity, precipitation gage for the measurement of heavy rainfall in isolated areas of the coastal ranges is described briefly. A standard gage is combined with salvage material to keep the cost low.

Upstream flood control studies for the Los Angeles River watershed have required additional precipitation data for the small areas at the heads of tributaries where orographic influences cause excessive precipitation at high intensities. Most suspected critical areas are in isolated locations accessible only by foot trail or by mountain roads not traversible during the periods of winter storms. An attempt was made in 1942 to expand the gage network, and some gages were operated through the 1944-1945 season in the Arroyo Seco area.

Our experience during the storm of January 1943 indicated the need for a storage type gage. The 12-inch capacity recording gages overflowed before they could be serviced. Although none of the standard gages overflowed, it was evident that major storms might cause these gages to overflow before observations could be made. Analysis of records from the gages at the isolated locations indicated a higher potential precipitation in the more remote areas, and increased capacity appeared even more necessary.

As a result of this need, a storage type gage was developed that could be constructed and installed at low cost. This gage consists of an overflow container made of a salvaged grease drum, with a cap and collar through which a standard rain gage protrudes (see Figs. 1 and 2). The cap is on a sponge rubber gasket and is sealed to the drum by its own weight. The collar joint is made watertight by a section of truck size inner tube slipped over the standard rain gage and covering the lip of the cap. A hole for overflow is cut in the standard gage below the storage can collar. The capacity of the gage is 60 to 70 inches of water, depending on the size of the available drum. A shield is not provided, as it is usually possible to clear a protected area in the brush to avoid direct wind.

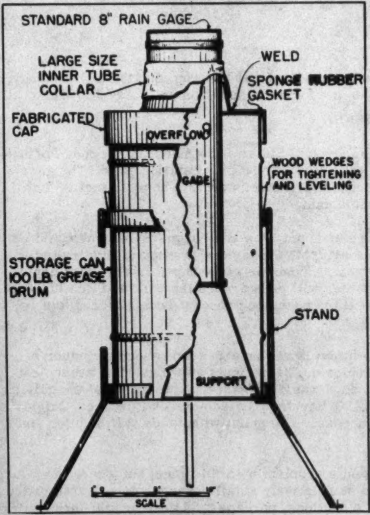
STANDARD 8" RAIN GAGE
LARGE SIZE INNER TUBE COLLAR
WELD
SPONGE RUBBER GASKET
FABRICATED CAP
OVERFLOW
GAGE
WOOD WEDGES FOR TIGHTENING AND LEVELING
STORAGE CAN 100 LB. GREASE DRUM
STAND
SUPPORT
SCALE

Fig. 1--Plans for storage-type precipitation gage

To date (since installation of storage gages in the fall of 1945) there has not been sufficient precipitation to require the additional storage provided. The storage cans have, however, caught unsuspected leakage in two standard gages.

Several of our present gages are located at higher elevations where some snow can be expected. In these places the funnel and measuring tube are removed, and the standard gage can is charged with a measured amount of commercial anti-freeze solution. Our choice of this melting agent was based on its availability in stock at our warehouses.

It is considered that the gage as now constructed has only a limited value for snowfall measurement and is dependable for snowfall to about 12 to 14 inches depth only. A 12-inch snowfall was caught in one gage with partially satisfactory melting by the anti-freeze solution. Apparently the reduced temperature of the fluid did not allow complete melting, and a crust formed supporting about two inches of unmelted snow.

During the current season, observations have been made after each storm, as most roads have remained open. The records already obtained in isolated spots are proving of value in the determination of relative precipitation and storm patterns.

Installation of these gages may prove useful in isolated mountain areas where convectional storms occur and where regular observations are not possible. The chief advantage of the gage is its ease of construction and its small cost, due to the use of salvaged materials. The assembly is light in weight and of small enough parts so that it can be transported by pack animal to distant areas. As an additional practical consideration, the unit is painted in camouflage colors to avoid presentation of an inviting target for the indiscriminating rifleman.

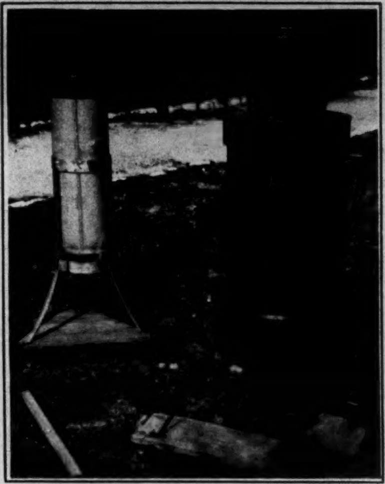

Fig. 2--Storage type and standard precipitation gages

U. S. Forest Service,
Flood Control Project,
Oak Grove Park,
Pasadena 2, California

(Manuscript received October 23, 1946; presented at the Regional Meeting, Section of Hydrology, Sacramento, California, February 28, 1946; open for formal discussion until May 1, 1948.)

DISCUSSION

Ashton R. Codd (United States Weather Bureau, Central Sierra Snow Laboratory, Soda Springs, California)--I see no objection Fittinger's design of a storage type precipitation gage. The gage apparently is meeting his needs and certainly is economical to construct. The main fact is that he is catching the precipitation and obtaining valuable data.

The problem of evaporation from the time of rainfall until the time of measurement would be very small due to the design. If this factor became evident, a measured portion of light cylinder oil could be placed in the bottom of the standard gage. A common ball-shaped fishing cork could be laid in the funnel of the standard gage; the rainwater will pass around the cork and into the gage. When the rain stops, the ball-shaped cork would seal the gage and evaporation is reduced to a minimum without using oil.

We have found that the standard anti-freeze solution is rather expensive where a number of gages are under operation. A solution of calcium chloride, 34 per cent by weight, has proven satisfactory and economical. If the salt solution is used, I would suggest that the inside of the galvanized case be given a coat of asphalt base paint. We have found a commercial product, Quigley's Triple A Black Protective Coating ideal for this purpose. This paint withstands salt solution and oil better than many other paints tried.

It is evident that the catch of snow would present a problem with this gage, but where the amounts are small and infrequent the losses would be relatively small. Where snow is anticipated as a consistent form of precipitation at the higher elevations, perhaps a 60-inch or 100-inch conical-shaped gage with a fairly large charge of calcium chloride and oil could be installed at those stations.

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VALUE OF THE ELECTRICAL LOG FOR ESTIMATING GROUND-WATER SUPPLIES AND THE QUALITY OF THE GROUND WATER

B. A. Barnes and Penn Livingston

(Published by permission of the Director, Geological Survey,
United States Department of the Interior)

Abstract--This paper gives a brief summary of studies of the value of the electrical log for estimating ground-water supplies and the quality of the water in them made in Texas by the United States Geological Survey and cooperating parties.

The electrical log has been found to be especially valuable in the Coastal Plain Region of Texas where the rocks consist mostly of a succession of clays or shales or sandy clays or shales interbedded with sands or sandstones. In that region the electrical log has been found to be more useful than the driller's log for correlating the principal water-bearing horizons over wide areas. The log by itself is not an indicator of the permeability of the water-bearing beds, nor a safe guide as to the quality of the water in them, but if it is studied in connection with other data, it is sure to tell an interesting and instructive story. Thus far in Texas no extensive studies have been made of the value of the electrical log in limestone aquifers or in sand or sandstone aquifers associated with limestone.

Introduction--Electrical logging of wells, developed in Europe, was first used in this country about 18 years ago in connection with explorations for gas and oil. In Texas electrical logs are now obtained in most oil and gas tests and in many deep water-well tests.

In electrical logging, devices are used which automatically record the values for the apparent resistivity and natural self-potential or Earth current in uncased wells. The electrical log is recorded to scale photographically and usually consists of two or more resistivity curves and a potential curve. The resistivity curves give a graphical record of the apparent specific resistances of the beds penetrated by a well. This record is obtained by measuring the potential drop of an induced current between known constant electrode spacings, and recording the values in ohms per square meter per meter. Most authorities agree that the resistivity of rocks in place depends largely on the conductivity of the contained fluid; size, arrangement, and size distribution of rock particles; degree of alteration, cementation, etc.; and possibly to some degree upon the mineral character of the rocks.

The self-potential curve is a record of values of the Earth current or natural self-potential that occurs spontaneously in the drilled hole. Several sources are responsible for the observed anomalies in this curve, of which, in water wells, the electrochemical effect produced by the drilling mud is believed to be most important.

A large number of books and papers have been written on the use and the interpretation of electrical logs [see "References" at end of paper, HEILAND, 1940; JAKOSKY, 1940; GUYOD, 1944 and 1945].

The electrical log is a valuable aid toward the solution of ground-water problems when it is supplemented by a good log obtained from the driller, and by general information regarding the character of the rocks and chemical quality of the water in them. A knowledge of the history of sedimentation in the particular area under consideration is important.

The electrical log is used in Texas to obtain information of a quantitative and qualitative nature in connection with ground-water investigations.

Quantitative use of the electrical log--The electrical log provides a more accurate record than the driller's logs of the occurrence and sequence of water-bearing beds, especially in unconsolidated sediments. However, although the values recorded by the resistivity and self-potential curves may accurately delineate the changes from sands to clays, sands to limestones, and other

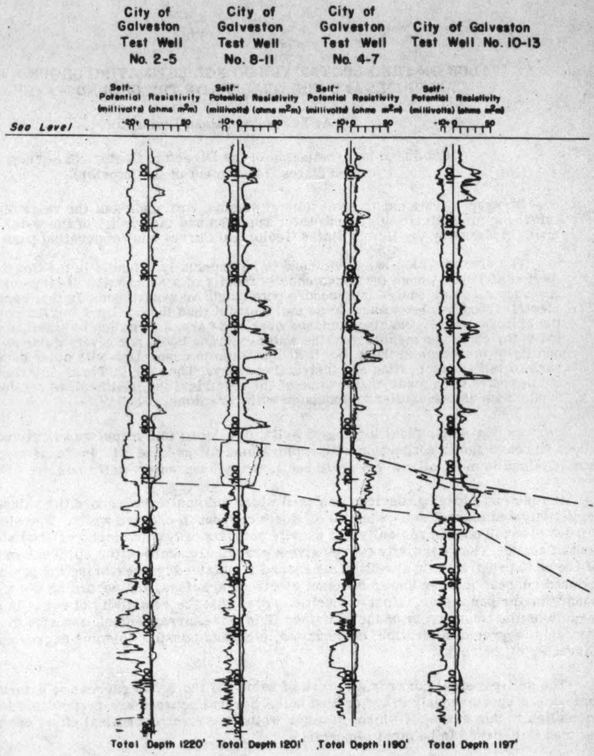


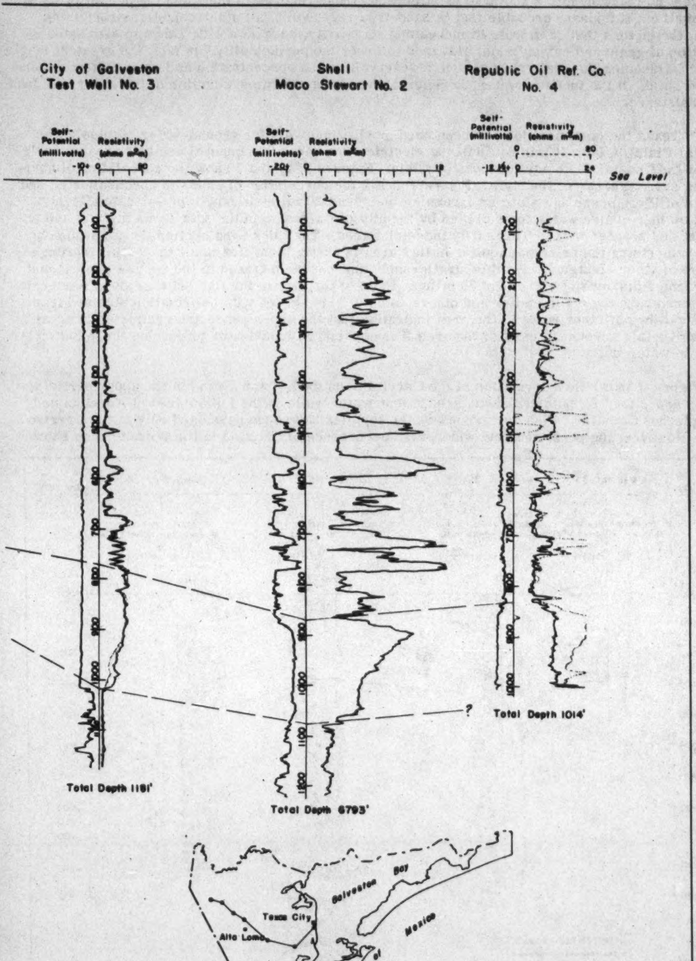
FIGURE I

CORRELATION OF AQUIFERS WITH ELECTRICAL LOGS GALVESTON COUNTY, TEXAS

Horizontal Scale

1 0 1 2 3 Miles

Depths below sea level in feet


City of Galveston
Test Well No. 3
Shell
Maco Stewart No. 2
Republic Oil Ref. Co.
No. 4
Self-Potential (millivolts)
Resistivity (ohms m²/m)
Sea Level
Total Depth 1181'
Total Depth 6793'
Total Depth 1014'
?
Texas City
Alta Loma
Galveston Bay
Gulf of Mexico
GALVESTON COUNTY

changes, no relationship is known to exist between these recorded values and the permeability of a formation. It appears probable that in sand-type reservoirs, all other conditions remaining equal, the factors that contribute to increasing resistivity, such as a wide range in size and distribution of grain and cementation, also tend to lower the permeability. In fact, the greatest single factor influencing the resistivity of such a reservoir is the concentration and character of the dissolved solids in the included water; in general, the higher the mineralization of the water, the less the resistance.

In Texas the electrical log has been used most extensively for ground-water studies in the Coastal Plain; in fact, it was not until the electrical log came into general use that areal correlation of the Coastal Plain aquifers was possible. Figures 1, 2, and 3 show the correlation of aquifers in several areas of the state. Figure 1 shows the correlation of sands in unconsolidated sediments of Pleistocene age along an irregular line about 20 miles in length in Galveston County, based on logs of five water tests drilled by the city of Galveston in the Alta Loma district and an oil test and a water well in Texas City industrial area. The thick sand section, basal Beaumont clay, comprising the principal aquifer in this area is easily identified in all the wells. Through the use of other electrical logs this stratigraphic unit has been traced to the north and northeast of the line a distance of more than 30 miles. Some of the logs in the line show sands of moderate thickness above the main aquifer and others do not. This agrees with information obtained from electrical logs of other wells in the area indicating that the upper sands are restricted in areal extent. On this account in most of the area it is considered inadvisable to develop these lenticular sands in water wells.

Figure 2 shows the correlation of the Carrizo sand (bed 1) and a sand in the upper part of the Wilcox group (bed 2), both of Eocene age, in four water wells in the Lufkin area of Angelina and Nacogdoches Counties. Thus far ground-water supplies have been developed only in the Carrizo sand. However, the persistent and widespread occurrence of the sand in the Wilcox group shown

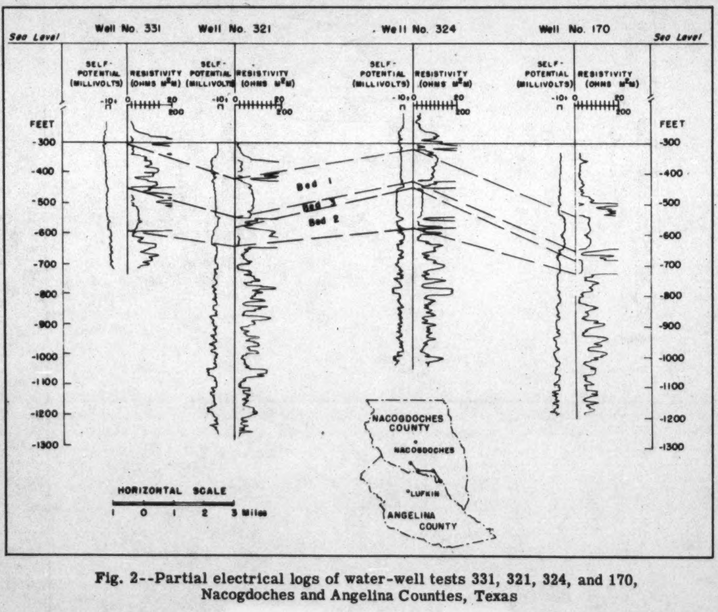

Sea Level
Well No. 331
Well No. 321
Well No. 324
Well No. 170
Sea Level
SELF-POTENTIAL (MILLIVOLTS)
RESISTIVITY (OHMS M²/M)
-10+
0
20
200
FEET
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
Bed 1
Bed 2
NACOGDOCHES COUNTY
NACOGDOCHES
LUFKIN
ANGELINA COUNTY
HORIZONTAL SCALE
1 0 1 2 3 Miles

Fig. 2--Partial electrical logs of water-well tests 331, 321, 324, and 170, Nacogdoches and Angelina Counties, Texas

by the electrical logs in these and other wells was so encouraging that plans were made to develop both sands in certain localities where the electrical log shows the sand in the Wilcox group is of sufficient thickness, and the water it contains is of suitable quality.

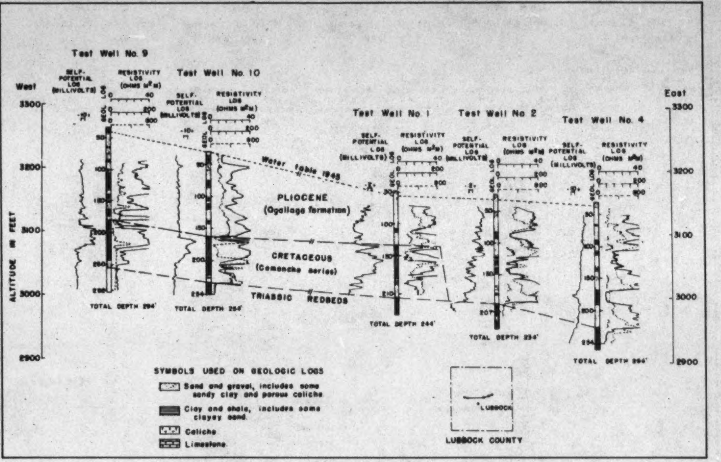

Test Well No. 9
Test Well No. 10
Test Well No. 1
Test Well No. 2
Test Well No. 4
West
East
SELF-POTENTIAL LOG (MILLIVOLTS)
RESISTIVITY LOG (OHMS M²/M)
GEOL. LOG
Water table 1945
PLIOCENE
(Ogallala formation)
CRETACEOUS
(Comanche series)
TRIASSIC REDBEDS
ALTITUDE IN FEET
3300
3200
3100
3000
2900
TOTAL DEPTH 294'
TOTAL DEPTH 294'
TOTAL DEPTH 244'
TOTAL DEPTH 234'
TOTAL DEPTH 294'
SYMBOLS USED ON GEOLOGIC LOGS
Sand and gravel, includes some sandy clay and porous caliche
Clay and shale, includes some clayey sand
Caliche
Limestone
LUBBOCK
LUBBOCK COUNTY

Fig. 3--Geologic section in Lubbock County, Texas

Figure 3 shows a geologic section in Lubbock County in the High Plains of Texas [LANG, 1945]. The section is based on logs of five test wells drilled by the city of Lubbock in connection with plans looking toward an increase of about ten million gallons of water a day for public supply and industrial use. The wells were drilled through the deposits of the Ogallala formation, which furnish most of the useable water in the High Plains region, into the underlying Cretaceous and Triassic rocks. One of the purposes of the exploratory program was to obtain information regarding the available supply of water in the basal Cretaceous sands and in sands in the upper part of the still deeper Triassic section. The basal Cretaceous is shown in both the electrical and the drillers' logs of wells 1, 9, and 10. In the logs of wells 2 and 4 the sand apparently is absent. The Cretaceous sands proved to be relatively thin or absent and the Triassic beds proved to consist dominantly of clay; therefore the plan to develop water in the Cretaceous and Triassic rocks was abandoned.

Qualitative use of the electrical log-- The use of electrical logs for qualitative purposes in ground-water investigations in Texas has come into limited use during the last four years chiefly for estimating changes in the chemical character of the water with depth in sand-type aquifers. Little is known concerning the qualitative significance of such logs obtained in limestone aquifers.

The qualitative interpretation of electrical logs is based on the fact that increasing salts in solution in the interstitial water causes decreasing resistivity, other factors remaining the same, and on the assumption that electro-chemical action is the major factor contributing to the self-potentials recorded on the electrical log. It is not possible from the change of anomalies on the electrical log to estimate the change in each of the salts in solution because of the different electro-chemical characteristics of each of the salts, but in any given area the changes in dissolved solids often can be confined to one or two of the salts, thereby permitting the anomalies on the electrical log to be interpreted, in this restricted sense, with moderate success.

For instance, in Galveston and adjacent counties along the Texas Gulf Coast the predominant variation is in the chlorides. In the Lufkin area (see Fig. 4), the predominant variation is in the small amount of bicarbonate in the water of the Carrizo sand compared with the large amount in the sands of the upper part of the Wilcox group.

The log of City of Lubbock test 10, in Figure 4, is a good example of the type obtained in the Ogallala formation of Pliocene age and underlying rocks of Cretaceous age in the southern High

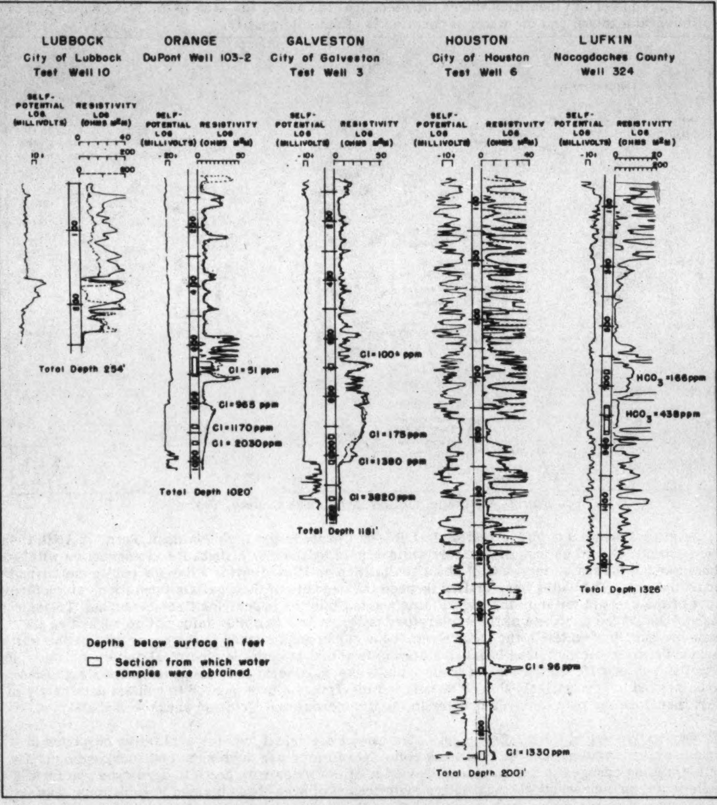


Fig. 4--Evidence of quality of ground water as shown by electrical logs of wells in five localities in Texas

Plains of Texas. No water samples were obtained from this test, nor is an analysis of a mud sample from the well available, and because of these facts a qualitative interpretation of the log is very difficult and must be made on a comparative basis only. The water used for drilling came from the Lubbock city supply and, therefore, only the lower limit of the general order of magnitude of dissolved salts in the mud was known. From the minor differences recorded on the self-potential curve of the log it appears that the water in the sands of the Ogallala formation between depths of 36 and 62 feet is similar to the water contained in the mud. In the basal Cretaceous sand section from about 221 to 236 feet the general increase in self-potential appears to indicate that the water in the sand is more highly mineralized than the water in the Ogallala formation. The slight increase in resistivity in the Cretaceous sand possibly may be caused by cementation of the sand.

The log of DuPont well 103-2 (see Fig. 4) is that of a test well near Orange, in Orange County, Texas. The log gives evidence that the sands from 572 to 725 feet contain fresh water, and this was confirmed by a water sample collected between 642 and 703 feet which contained only 51 ppm of chloride. Underlying the fresh water sand is a clay about 80 feet thick, from 725 to 800 feet below the surface. Below this separating clay is a thick sand extending from about 800 to 970 feet below the surface, which the log indicates as containing much more highly mineralized water than the water in the overlying sands. In addition to the higher mineralization the log indicates the existence of a vertical concentration gradient of increasing salts with depth. Proof of this gradient is shown by the analysis of three samples obtained from depths of 809 to 820 feet, 872 to 883 feet, and 930 to 941 feet containing chlorides of 965, 1170, and 2030 ppm, respectively.

The third graph in Figure 4 is a reproduction of the electrical log of test well No. 3 of the City of Galveston, located near Hitchcock in Galveston County, Texas. From analyses of water samples from several nearby screened wells, in sands about 700 feet below the land surface, it was known that the water in the uppermost part of the main sand contained about 100 ppm of chloride. From 930 or 940 feet to the base of the sand at 1023 feet the log shows a rapidly decreasing resistivity, indicating increasing mineralization of the water. To confirm this, one water sample was obtained from a depth of 930 to 940 feet, and another from the base of the sand between 1015 and 1023 feet. The upper sample contained 175 ppm and the lower sample, 1380 ppm of chloride. The log indicated that the water in sands below the base of the main aquifer at 1023 feet was still more highly mineralized. This was confirmed by a sample obtained from the sand at 1140 to 1152 feet, which contained 3820 ppm of chloride.

The fourth graph in Figure 4 is a reproduction of the electrical log of City of Houston test well No. 6, near Clodine, Harris County, Texas. From the surface to about 1973 feet this log shows the usual anomalies that are common to the fresh water zones in this area. The sand from 1973 to 2001 feet, however, shows a decided increase in self-potential and a corresponding decrease in resistivity indicating a material increase of chloride as compared with the water in the sands above. Two water samples were obtained from this well; one from the sand between about 1675 and 1705 feet, contained 96 ppm of chloride, and the one from the sand between 1973 and 2001 feet contained 1330 ppm of chloride.

Figure 4 includes the electrical log of well 324 in Nacogdoches County, an exploratory well drilled in connection with the development of a large supply of ground water for industrial use near Lufkin, Texas. The log affords a good example of the effect of dissolved salts other than chloride. In this log two thick sand sections, separated by a clay about 20 feet thick, are shown between 620 and 880 feet below the surface. The upper section is the Carrizo sand, while the lower one is a sand in the Wilcox group. Partial analyses of water samples collected from each of these sand sections show that the waters are of similar chemical character with the exception of the bicarbonate. The water from the Carrizo sand contained 220 ppm of total solids, with 166 ppm of bicarbonate, while water from the lower section of the sand in the Wilcox group contained 550 ppm of total solids, with 438 ppm of bicarbonate. Both samples contained 16 ppm of chloride. The lesser resistivity and greater self-potential shown by the sand in the Wilcox group as compared with the Carrizo sand is indicative of the difference in the bicarbonate in the water.

Figure 5 shows the correlation of the electrical log with the geological log of a water well at the McCloskey General Hospital at Temple, Texas. The geological log was compiled by F. B. Plummer of the Bureau of Economic Geology of the University of Texas and by Mrs. Plummer from an examination of the drill cuttings and cores. The electrical log is a typical example of such logs as obtained in the Cretaceous rocks of the central Texas area. It starts in the Austin chalk of the Upper Cretaceous series and ends a few feet below the bottom of the Pearsall formation (Travis Peak), basal formation of the Cretaceous system of central Texas. The correlation of these two logs illustrates the advantages and limitations of the electrical log.

Of interest is the fact that the Plummers found no indication of the Buda limestone in the drill cuttings, although aware that the formation is present in this area. The electrical log, however, shows a dense bed about five feet thick at about 590 feet below the surface. This is believed to be the Buda limestone which was missed in the collection of drill cuttings. Below the Buda the Grayson shale (Del Rio clay), Georgetown, Edwards, and Comanche Peak limestones, Walnut clay, and Glen Rose limestone show the characteristic anomalies of these formations in the central Texas area and correlate fairly well with the geologic log of the Plummers. The contact between the Glen Rose limestone and the underlying Pearsall formation (Travis Peak), however, is very difficult to determine from the electrical log alone, probably because the contact consists of a gradational zone.

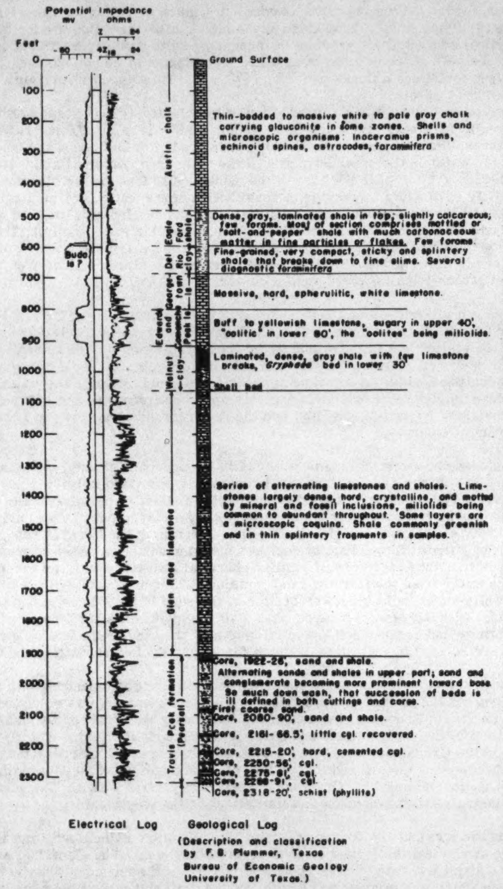


Fig. 5--Correlation of electrical and geological logs of water well at McClosky General Hospital, Temple, Texas

Summary

The electrical log has proven its value in estimating ground-water supplies and the quality of the ground water in Texas, especially in the Coastal Plain region where the rocks consist mostly of a succession of clays or shales, or sandy clays and shales, interbedded with sands or sandstones.

In that region the electrical log has been found to be more useful than the driller's log for correlating the principal water-bearing horizons over wide areas. The log itself is not an indicator of the permeability of the water-bearing beds, nor a safe guide as to the quality of the water in them, but if it is studied in connection with other data, it is sure to tell an interesting and instructive story. For example, in interpreting the log it is vital to know the chemical character of the drilling mud at all times during the drilling and to have a good general knowledge of the lithological character and structure of the rocks and the quality of the water in them at different depths.

Thus far no very extensive studies have been made in Texas of the value of the electrical log in limestone aquifers or in sandstone aquifers associated with limestone. In several cases, however, in such areas the log has proven to be valuable when it was supplemented by a geological log, based on a study of drill cuttings or core samples.

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United States Geological Survey,
Austin, Texas

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Transactions, American Geophysical Union Volume 28, Number 6 December 1947

EFFECT OF TRAIN LOADING ON THE WATER LEVEL IN A DEEP GLACIAL-DRIFT WELL IN CENTRAL ILLINOIS

W. J. Roberts and H. E. Romine

Abstract--The paper presents additional detailed information on the effect which a known surface loading has on the piezometric water surface of a confined aquifer. The reaction of the water surface to the loading and unloading effects of passing railroad trains of different weights, moving at varying speeds, is measured with a specially constructed sensitive water-level recorder.

The variation in the observed artesian pressure caused by the movement of trains past a water well has been long noted by hydrologists. The earliest published observations of this phenomenon were made in 1892 by KING [see "References" at end of paper, 1892]. Using a very crude recording mechanism, he was able to detect small rises in water level in a six-inch cased well 40 feet deep and located 140 feet from a railroad track. One of the most detailed published accounts of water-level fluctuations produced by passing railroad trains was made by JACOB [1939] in 1937. His studies of the effect of railroad trains passing near a well at Smithtown, Long Island, shed considerable light on the effect of such loading on the pressure distribution within an elastic artesian aquifer.

In the present study an attempt is made to show the effect of train loading on the water level in an isolated well of high "barometric efficiency" penetrating a confined aquifer. A well with these characteristics is located in east central Illinois on the right-of-way of the Illinois Central Railroad. The well is 60 feet west of the center line of the southbound track.

The well was drilled in 1944 to supply water for the construction of the airport of the University of Illinois. After the runways were completed in the late fall of 1945, the pumping equipment was removed and since that time intensive observations have been made on water-level fluctuations produced by more than 120 passing railroad trains.

The well is 169 feet in depth below ground level and is cased with eight-inch pipe. Thirteen feet of 7.5-inch diameter wire-wound, No. 50 slot screen is exposed to the aquifer. Total depth of the well from top of casing to bottom of screen is 171 feet. Normal water level is about 70 feet below ground surface elevation of 735 feet above mean sea level. The water-producing horizon is 15 feet of glacial sand and gravel bedded on shale of the Pennsylvanian system and overlain by 154 feet of tight impervious silt, till and soil. This formation is relatively continuous over a wide area in central Illinois, and where the deposit of sand and gravel has high permeability it is capable of supplying large amounts of water. Electrical earth resistivity surveys and interpretation made by the Illinois Geological Survey (see Fig. 1) "suggest the presence of a thin lens of sand and gravel which has its thickest development in the vicinity of the well. The data suggest that the material passes laterally into water-laid slightly permeable clayey silts in all directions from the zone of maximum development. It is likely that the deposit is much thinner and of less permeable texture near its margins than in the center of the area and that the arbitrarily selected boundary is indicative of the approximate position of a rather broad gradational zone in the change from coarse to fine texture."

A five-hour production test of the observation well indicated that the well was capable of producing 250 gpm with a drawdown of 14.5 feet. For a five-month period the well was pumped at a rate of 150 gpm, ten hours per day. The nearest pumped well that penetrates this aquifer is a two-inch farm well located more than 1,000 feet south of the observation well.

In April 1945 the Illinois State Water Survey, as a part of its program of evaluating the water resources of the State, installed a standard Stevens type F water-level recorder having a 1:1 gear ratio. Seven-day chart records of the piezometric surface indicated a normal response (for the area) to atmospheric pressure changes, but some distrubances that could be explained only as the effect of passing trains were also noticeable on the charts. Figure 2 shows a typical chart and a record of barometric pressure (four miles north at Urbana) inverted and plotted in feet of water.

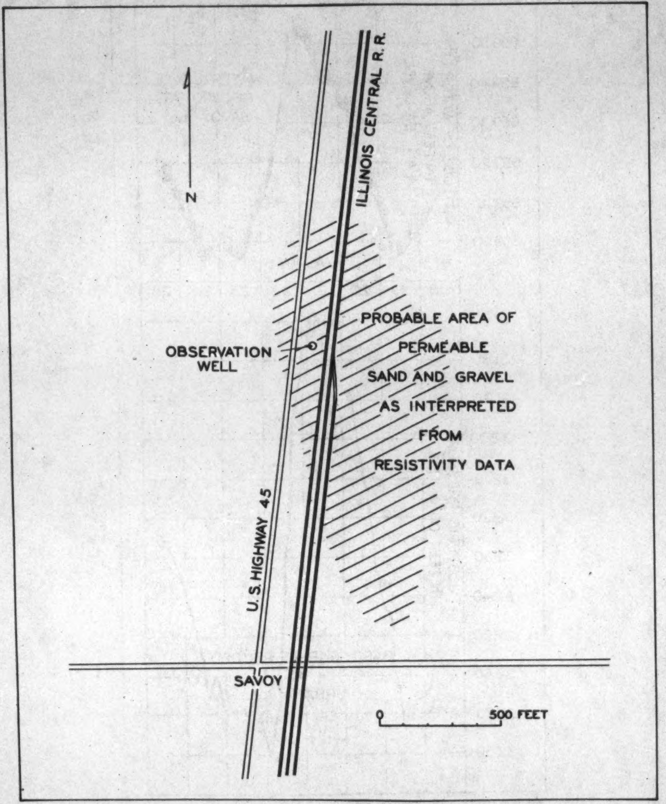
N
ILLINOIS CENTRAL R.R.
PROBABLE AREA OF PERMEABLE SAND AND GRAVEL AS INTERPRETED FROM RESISTIVITY DATA
OBSERVATION WELL
U.S. HIGHWAY 45
SAVOY
0
500 FEET

Fig. 1--Map showing location of observation well near Savoy, Illinois

The barometric efficiency of the well is 50 per cent which is about an average figure for properly constructed tubular wells in this aquifer.

Since the time intervals of a passing train were so slight in comparison to the normal movement of the recorder pen on the time scale of even a 24-hour chart it was decided to rebuild a recorder to provide a pen movement of about two inches per minute. A description of the apparatus is incidental, but an electric drive was used to effect continuous operation of the recorder for extended periods of observation. Refinements of the equipment included reduction of frictional lag in the recorder, bailing of the well to remove all surface material and centering of the float in the well. The recorder was mounted on a clamp attached to the well casing in order to eliminate any effect of ground movement.

Generally, all trains, whether northbound or southbound, were moving at their greatest speeds when they passed the well. Speeds ranged from that of slow 100-car coal trains to that of fast

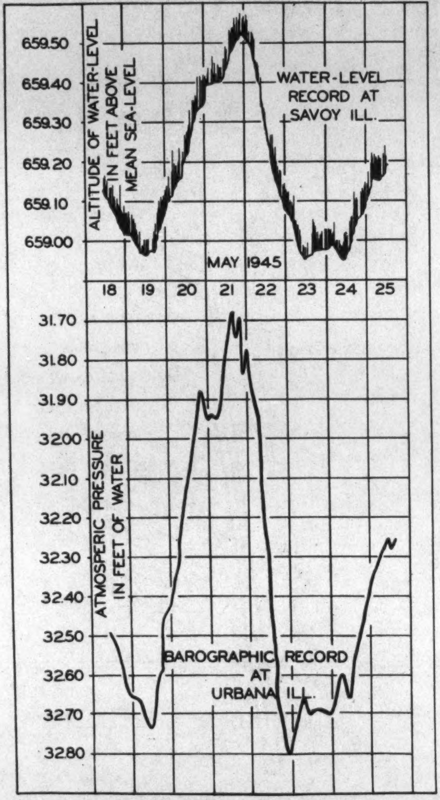

Fig. 2--7-day record of barometric pressure and water level in observation well

streamliners. A timing system was developed so that train velocity could be computed fairly accurately and correlated with recorder-pen movement. This was most important, for it was soon apparent that the speed of the train was a factor in determining the magnitude of the rise of the piezometric surface shown by the water-level recorder.

The difference in effect of southbound and northbound trains became apparent during the earlier observations. The nothbound freight trains, generally loaded coal or oil cars, caused a smaller water-level rise than that caused by empty southbound trains. Three factors contribute to this difference: (1) The northbound track, although only 15 feet east of the southbound track is 20 per cent more distant from the well than the southbound track. (2) The northbound track has a 131-lb rail compared to 112-lb rail for the nearer southbound track. (3) The northbound track was reballasted in the spring of 1945 with six inches of fresh ballast whereas the southbound track has not been worked for two years and in that length of time it has compacted 25 per cent. The difference in observed effect between northbound and southbound trains is probably due to the cushioning effect of the heavier rail on the more recently ballasted track, as the magnitude of this difference decreased with time as the ballast compacted.

Before analyzing the recorder charts of individual trains one important factor must be noted. Trains approaching from the north at normal running speeds cause the water level in the well to rise to its highest position when the front end of the engine is about 75 feet north of the well. Northbound trains cause no appreciable change on the recorder chart until the front end of the engine is opposite the well. There appears to be an area along the track centered at a point 50 to 75 feet north of the well where the load is most readily transmitted to the aquifer. On slow-moving trains, one to five mph, the effect is more widespread, that is, the water level in the well starts rising when the engine of a southbound train is between 400 and 500 feet north of the recorder house and when the engine of a northbound train is 300 to 400 feet south of the well. Thus the total rise in water level is influenced by a combination of factors such as the speed of the train, its length, load, and the distribution of that load.

A typical curve produced by passage of a northbound freight train is shown in Figure 3. Generally the initial rise caused by passage of the engine is sustained or augmented by the following loaded cars. The rise in water level is generally greatest with approach of the engine, and a gradual decline takes place as the empty cars pass. When a mixed freight train passes southward there is generally a fluctuation in the well-water level that corresponds closely with the passage of empty and loaded cars, as is shown in Figure 4. The southbound track, apparently because of the greater compaction of the ballast, is more sensitive in transmitting slight changes in load.

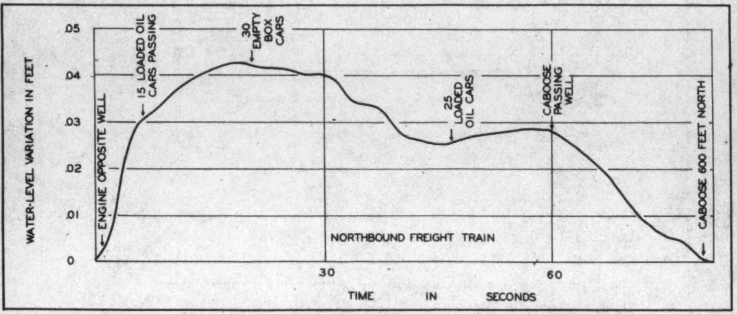

Fig. 3--Water-level fluctuation produced by northbound freight train

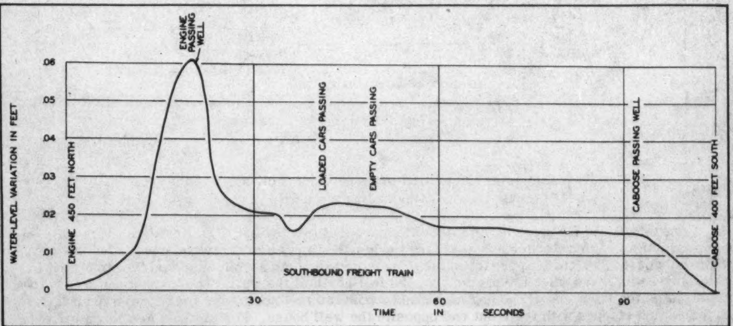

Fig. 4--Water-level fluctuation produced by southbound freight train

Another factor that has been studied is the depression of the ground by passing trains. Careful measurements have been taken by observers with levels located 500 feet west of the tracks and it was found that for load intensities ranging up to 3.3 tons per foot of track the effect on the ground elevation at the toe of the embankment and the recorder house was negligible.

Occasionally a switch engine had stopped opposite the well and the recorded rise in water level remained constant for the part of a minute that the engine had been stationary. In order to examine this effect further, arrangements were made to have certain trains make special runs past the well.

Figure 5A is a record of water-level fluctuation taken during the passing of a local freight train composed on an engine and tender (with a combined weight of 262.5 tons) and 35 cars. During the five-minute period when the engine remained stationary, the recorded rise in piezometric surface remained constant until the train moved on.

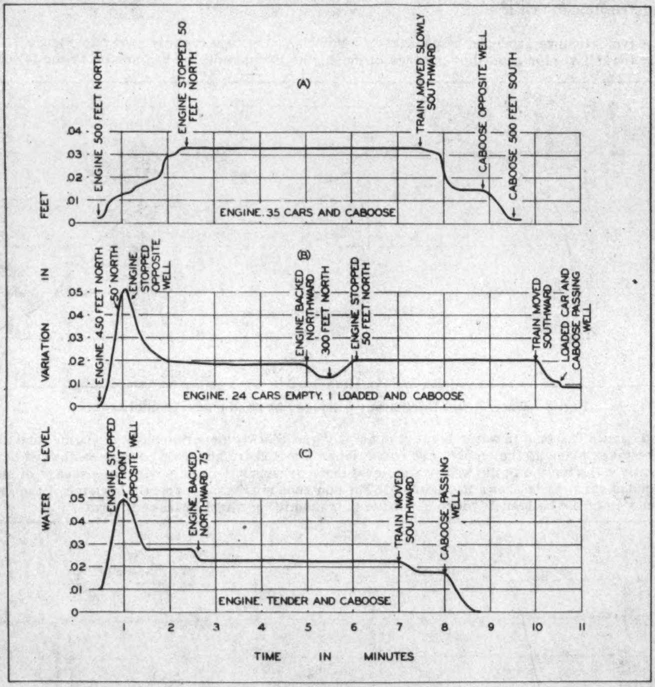

Fig. 5--Water-level fluctuation in observation well produced by special train-loading tests

Figure 5 (B and C) records the effect of passage of two trains. The first train (Fig. 5B) was composed of an engine, tender and auxiliary tender, 24 empty box cars, and one loaded car next to the caboose. This train approached the area from the north at four mph and the first rise in water level was noted when the engine was 450 feet north of the well. The highest water level was recorded as the front end of the engine passed a point 50 feet north, and there was a drop in level as the engine stopped with the front end opposite the well house. For one minute the water level continued to decline from a maximum rise of 0.05 and then remained constant at a stage of 0.02

feet above the base line. After three minutes the train was backed up 300 feet northward and then was moved forward so that the front end of the engine stopped 50 feet north of the well. Although the net recorded rise in water level did not equal the original rise as the train had first approached, the rise of the water surface was maintained until the train moved southward four minutes later.

The second train (Fig. 5C) followed four minutes after the departure of the first and was composed of an engine of same weight and class as the first engine, a tender, auxiliary tender, and caboose. It approached the area from the north at four mph and caused the water level to start rising when it was 450 feet north of the well. The engine stopped with its front end opposite the well, and the same decline of water level was noticed for about 20 seconds after which the level remained constant. The engine then moved backward 75 feet, during which time there was a slight decline in water level; but when the engine stopped, the well-water level remained constant. After 4 1/2 minutes the train again moved southward and the water level returned to the level observed before the first train approached the area.

It is noted that while the second train was approaching, the first train was standing with its caboose 600 feet south of the recorder house. Also the second train had stopped 650 feet north of the well while waiting for the first train to move away from the area of observation. Thus there was some load retained on the aquifer between the passage of the two trains and this is reflected in the somewhat smaller relative rise in water level caused by the approach of the second engine even though its weight was the same as the first engine. Also the fall in water level after the second train passed southward was greater than the recorded rise by an amount almost equal to the difference in initial rises in water level produced by the passage of the two trains.

Attempts have been made to correlate the data obtained during this study, but the many unknown geologic and hydrologic factors plus the variation in loads prevent the inclusion of any mathematical analysis in this paper. The authors present this paper in the hope of drawing constructive criticism that may lead to a clearer understanding of the observed phenomena.

The greater part of this investigation would have been impossible to carry out without the interest and excellent cooperation of the personnel of the Illinois Central System who arranged their schedules to make available the trains used during the special tests.

References

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JACOB, C. E., Fluctuations in artesian pressure produced by passing railroad trains as shown in a well on Long Island, New York, Trans. Amer. Geoph. Union, Pt. 4, pp. 666-674, 1939.

Illinois State Water Survey,
Urbana, Illinois

(Manuscript originally received April 29, 1946, and revised on November 29, 1946; presented at the Twenty-Seventh Annual Meeting, Washington, D. C., May 27, 1946; open for formal discussion until May 1, 1948.)

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Transactions, American Geophysical Union Volume 28, Number 6 December 1947

THRUST FAULTS AND RELATED STRUCTURES IN EASTERN CUBA

T. P. Thayer and Philip W. Guild

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Abstract--Detailed areal mapping in central Camagüey Province and reconnaissance mapping in northern and eastern Oriente Province, Cuba, have revealed two major structural zones: (1) A zone of intense deformation, including thrust faulting, which lies north of the geographic axis of the island; and (2) a belt of domical mountains bounded on the north by Nipe Bay and the coast, and on the south by the Cauto trough and Guantánamo basin.

In Camagüey, extensive masses of serpentine and overlying tuffs have been complexly folded and overridden from the north by a block, at least 25 miles long, of limestones that form the Sierra de Cubitas and Sierra de Camaján. The overthrust carried a northern facies of Cretaceous and Eocene limestones over a southern facies of tuffaceous rocks of similar age, and had a displacement of at least six miles. In places serpentine was thrust over younger formations, and most of the shearing in the serpentine is attributed to diastrophism. A thrust zone exposed in Loma La Vigía, 15 miles north of Holguín, suggests a similar tectonic history for northern Oriente Province. Chaotic giant breccias that include waterlaid debris indicate that the overthrusts moved across the ancient land surface in both Camagüey and Oriente districts. The folding apparently began in the Cretaceous and culminated in overthrusting during early middle Eocene time. Post-Eocene deformation appears to be limited to warping or doming to maximum angles of about 20 degrees.

The zone of domical mountains is somewhat more than 100 miles long from east to west by 25 to 30 miles wide, and comprises three main units: (1) the Sierra de Nipe and (2) Sierra del Cristal domes, principally of serpentine; and (3) the Cuchillas uplift, which includes the Cuchillas de Toar and Sierra de Purial, composed of serpentine and pre-serpentine rocks. These uplifts are overlapped progressively on all sides by sediments ranging in age from Upper Cretaceous to Oligocene and Miocene, the older beds in places being highly folded. The mountains owe their present relief of 2000 to 4000 feet to the doming of an extensive erosion surface in the late Pliocene or early Pleistocene. The north and east flanks of the Cuchillas uplift extend below sea level, and drowned streams and elevated coral reefs show regional instability since the last major doming.

Introduction

The serpentinized peridotite which extends almost the entire length of Cuba has been generally recognized as an important element in the structure of the island, and much discussion has centered around its age and relations to the other rocks. Numerous investigators, beginning with HAYES, VAUGHAN, and SPENCER [see "References" at end of paper, 1901], have described the serpentine as occurring along axes of anticlinal folds, but estimates of its age have ranged from Cretaceous to middle Tertiary. Interest in the lateritic iron-ores led to rather detailed investigations of some limited areas of serpentine, particularly with regard to the formation of the laterites, by KEMP [1915], LEITH and MEAD [1911], CUMINGS and MILLER [1911], and others. The principal published contributions to the geology of the northeastern part of the island in recent years are by a group from the University of Utrecht, and are mainly of a reconnasissance nature [MAC GILLAVRY, 1937; KEIJZER, 1945]. The first extensive detailed study of the serpentines themselves was made between 1940 and 1945 by geologists of the United States Geological Survey as part of its wartime chromite investigations, the work being carried out under the auspices of the Interdepartmental Committee on Scientific and Cultural Cooperation with funds provided by the Department of State and the Foreign Economic Administration. The Camagüey district was mapped on a scale of 1:48,000 by FLINT, DE ALBEAR, and GUILD (in press), and parts of Oriente Province were reconnoitered by Guild and Thayer with the aid of aerial photographs taken by the United States Navy and the United States Army Air Forces. At the same time, the manganese deposits of Cuba were investigated and a large part of southern Oriente Province was mapped by PARK, [1942]; PARK and COX, [1944]; WOODRING and DAVIESS, [1944]; Straczek, Simons, and Lewis. The manganese investigations in the area south of the Sierra de Nipe contributed much information on the relations of the serpentine there.

Two major structural zones related to the serpentine were recognized: (1) A zone of strong deformation, including thrust faulting, which lies north of the geographic axis of the island and goes out to sea north of Nipe Bay; and (2) a zone of domical mountains bounded on the north by Nipe Bay and the coast, and on the south by the Cauto trough and Guantánamo Basin (see Fig. 1).

Zone of strong deformation

Camagüey district--The Camaguey and Holguín districts lie entirely within the zone of strong deformation, and although they occupy only a small part of it are believed to be representative of the zone as a whole. The major structural relations in the Camagüey district (see Fig. 2) appear to be relatively simple. An ultramafic complex, of which serpentinized peridotite is the dominant part, is intrusive into old metamorphic rocks, and is overlain unconformably by Cretaceous and younger rocks. Two volcanic rock units were recognized by MAC GILLAVRY [1937]: the "Tuff Series," mostly Upper Cretaceous in age, though the base is probably early Cretaceous; and an upper unit which is unconformable on the "Tuff Series" and is correlated with the Habana formation [PALMER, 1934] of Maestrichtian (latest Cretaceous) age.

Detrital fragments of quartz diorite from a stock that intruded and metamorphosed the lower rock unit in the vicinity of the city of Camagüey have been found in the Maestrichtian rocks. Serpentine fragments also were identified in these rocks, and the areal distribution of the formations indicates that the ultramafic complex antedates the "Tuff Series" as well. In the area mapped the Cretaceous and younger rocks overlap the margins of the complex on all sides except the northwest, and occupy an arcuate synclinal belt that crosses the center of the district. This syncline appears deep and is probably very complex, for although bedding in the tuffs dips steeply in many places, small masses of gabbro and serpentine crop out in the center of the structure.

The serpentine is bounded on the north by an overthrust fault which has been traced about 25 miles along the southern margin of the Sierra de Cubitas and is believed to underlie the Sierra de Camaján. These mountains are composed of limestones, more or less contemporaneous with the volcanic rocks, which represent a northern, marine facies of deposition. Although the thrust fault was not seen, its position is revealed by the relations along the front of the Sierra de Cubitas and within the Sierra de Camaján, and extensive exposures of fault breccias.

From Loma Tuabaquey (two miles east of Cuatro Caminos) westward, the south front of the Sierra de Cubitas trends about N 50° W; in places it rises abruptly as a scarp from the serpentine savannah, elsewhere low parallel ridges lie at the foot of the main escarpment, which attains a maximum height of about 700 feet. The limestones dip southward, rather gently within the range and steeply along the front; northwest of Banao the beds at the base of the scarp are overturned and dip 75° northeastward. The outermost ridges that extend southeastward from Banao consist of vertical lower and middle Eocene limestones which overlie the Cretaceous rocks making up the bulk of the range. Southeast of Loma Tuabaquey the front of the sierra swings east and breaks up into a series of irregular spurs which appear to correspond to fault blocks.

The structure of the Sierra de Camaján is more complex. Remnants of two thrust blocks, not distinguished on the map, rest on downfolded volcanic rocks of the southern facies, which in turn lie on serpentine. The lower block, which forms the southern and eastern part of the range, is composed of Upper Jurassic [IMLAY, 1942] and Lower Cretaceous [MAC GILLAVRY, 1937] thin-bedded fossiliferous limestones. A fenster in this block exposes the underlying tuffs. Thick-bedded Upper Cretaceous limestones, very similar to those of the Sierra de Cubitas, are exposed in the northern and western part of the range, and form numerous isolated outliers on the older limestones in the southern part. They dip nearly vertically, although in most places the underlying thin-bedded rocks dip at moderate or low angles. The two blocks together are believed to be a klippe, or outlier, which has been separated from the main Cubitas thrust block by erosion.

Direct evidence of faulting along the base of the Sierra de Cubitas is shown by extensive brecciation of the serpentine. Northwest of Banao the serpentine just south of the limestone contact is thoroughly brecciated, and consists of recemented angular fragments; cherty material is also common. Marked angularity of the fragments indicates crushing that was very different from the "pasty" shearing usually found in serpentine. The serpentine breccia is best exposed in a 15-acre area about 3.5 miles east of Cuatro Caminos. There a broad reentrant in the foothills of the range, nearly surrounded by structureless limestones, is floored with unstratified serpentine breccia that superficially resembles glacial till. The fragments range in size from blocks a foot or two in diameter down to fine sand, and consist mainly of serpentinized peridotite, with an admixture of gabbroic rocks and scattered small pieces of white limestone. The contact between the breccia and limestone is very sinuous, appears to be nearly horizontal, and is marked by a

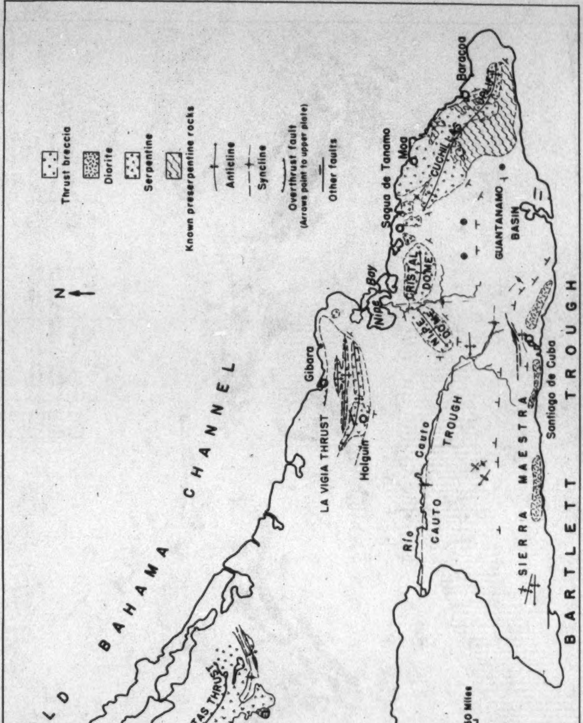
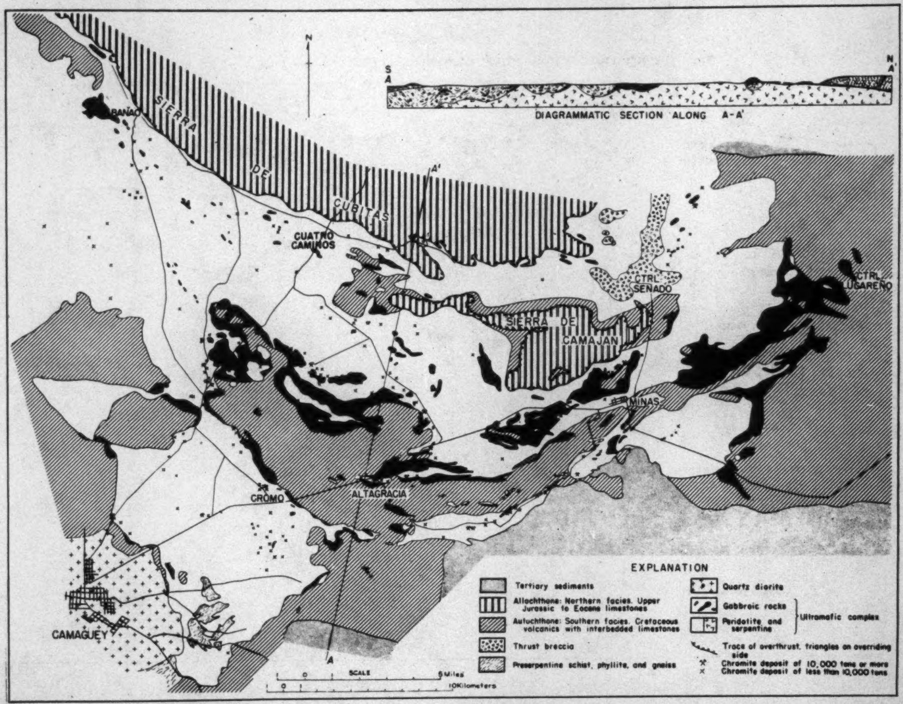

Thrust breccia
Diorite
Serpentine
Known preserpentine rocks
Anticline
Syncline
Overthrust fault
(Arrows point to upper plate)
Other faults
N
OLD BAHAMA CHANNEL
CUBITAS THRUST
Camagüey
LA VIGIA THRUST
Gibara
Holguín
Nipe Bay
Sagua de Tanamo
Moa
Baracoa
CUCHILLAS
CRISTAL DOME
NIPE DOME
GUANTANAMO BASIN
Río Cauto
CAUTO TROUGH
SIERRA MAESTRA
Santiago de Cuba
BARTLETT TROUGH
0 10 20 30 40 50 Miles

Fig. 1--Some major structural features of eastern Cuba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DIAGRAMMATIC SECTION ALONG A-A'
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MINAS
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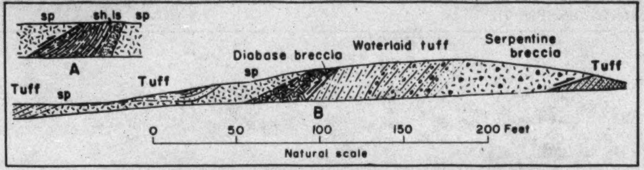
A
SCALE
0
5 Miles
10 Kilometers
EXPLANATION
Tertiary sediments
Allochthone: Northern facies. Upper Jurassic to Eocene limestones
Autochthone: Southern facies. Cretaceous volcanics with interbedded limestones
Thrust breccia
Preserpentine schist, phyllite, and gneiss
Quartz diorite
Gabbroic rocks
Peridotite and serpentine
Ultramafic complex
Trace of overthrust, triangles on overriding side
Chromite deposit of 10,000 tons or more
Chromite deposit of less than 10,000 tons

Fig. 2--Geologic map of the Camagüey chromite district, Cuba notable concentration of cherty silica. Exposures of massive serpentine less than half a mile to the southeast and the apparent low dip of the contact suggest that the breccia is between 20 and 50 feet thick.

Serpentine thrust over younger limestone and shales is well exposed in the north bank of the Río Máximo, six miles east of Cuatro Caminos (see Fig. 3). The basal beds lying on the serpentine consist of subangular fragments of serpentine in a matrix of carbonate and grade upward through sandstone into shale and limestone. A few pieces of serpentine were found in the limestone. The beds dip 35 to 65° SW under serpentine, and the upper contact is a well-defined fault that dips about 40° SW. About two miles to the northwest, in a side road, similar relations are indicated by fine-grained sandstones and mudstones interlayered with sheared serpentine. The sandstone was traced by float about 1000 feet northwest of the road along the strike; it is about six feet in greatest thickness and dips about 45° SW, parallel to the shearing in the serpentine. Thin sections show that the bedded material consists of well-rounded and well-sorted unweathered serpentine grains cemented by calcite without appreciable replacement. Float fragments of similar bedded material were found a few hundred feet southeast of the main breccia exposures. The limestones involved in these reverse faults have not been dated, but they resemble the Paleocene (?) Cangilones limestone which covers an extensive area a short distance to the east, and tentatively are regarded as similar in age [see DE LABEAR, in press].


sp
sh,ls
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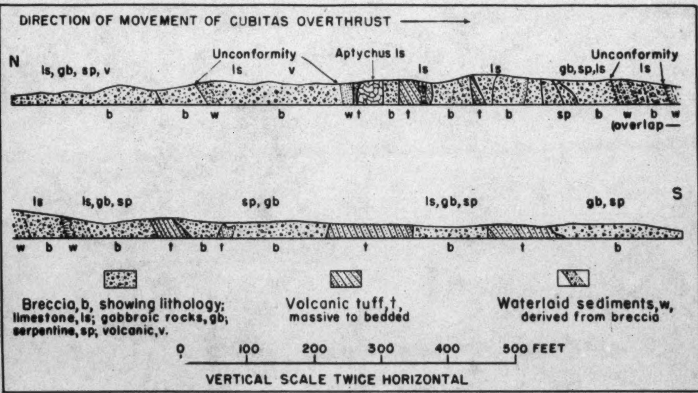
A
Tuff
sp
Tuff
Diabase breccia
sp
Waterlaid tuff
Serpentine breccia
Tuff
B
0
50
100
150
200 Feet
Natural scale

Fig. 3--Thrusting of serpentine over younger rocks in Cuba: (A) Over unconformable marine shales and limestones, Río Máximo, Camagüey; (B) over tuffs containing serpentine boulders, in cut on Gibara road 3.5 miles north of Holguín, Oriente Province

An area of ten to twelve square miles in the vicinity of Central Senado, east of the Sierra de Cubitas and northeast of the Sierra de Camaján, is underlain by an extraordinary mixture of serpentine and gabbro, tuff, and limestone. A 2000-foot cut on the Senado railroad about 1 1/2 miles north of the sugar mill shows that the rocks are divided into distinct units or blocks that are more or less homogeneous and are bounded by faults (see Fig. 4). The units consist of tuff, of brecciated


DIRECTION OF MOVEMENT OF CUBITAS OVERTHRUST ⟶
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Unconformity
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Aptychus ls
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b
Breccia, b, showing lithology;
limestone, ls; gabbroic rocks, gb;
serpentine, sp; volcanic, v.
Volcanic tuff, t,
massive to bedded
Waterlaid sediments, w,
derived from breccia
0
100
200
300
400
500 FEET
VERTICAL SCALE TWICE HORIZONTAL

Fig. 4--Generalized section of breccias exposed in railroad cut north of Central Senado, Camagüey, Cuba limestone or serpentine, and of mixtures of serpentine, gabbro, and limestone in any proportions. Viewed on a large scale, these units form a giant breccia. The bedding in the blocks of volcanic tuff dips uniformly southward at angles ranging up to 80° and in general it is only slightly folded, indicating relatively mild internal deformation. Blocks of tuff occupy about 20 per cent of the total area exposed in the walls of the cut. A 30-foot unit of highly contorted thin-bedded aptychus limestone, and a 50-foot unit of brecciated serpentine are exposed in the east wall of the cut. Most of the breccia, as shown in Figure 5, consists of an unsorted or rudely stratified mixture of large blocks ranging up to four feet in diameter in a matrix of fine-grained serpentinous, clayey or limy material, and resembles glacial till (see Fig. 6). In places the breccia approaches fault gouge in character, and blocks of limestone have been sheared out into elongate lenses of granular material (see Fig. 7).

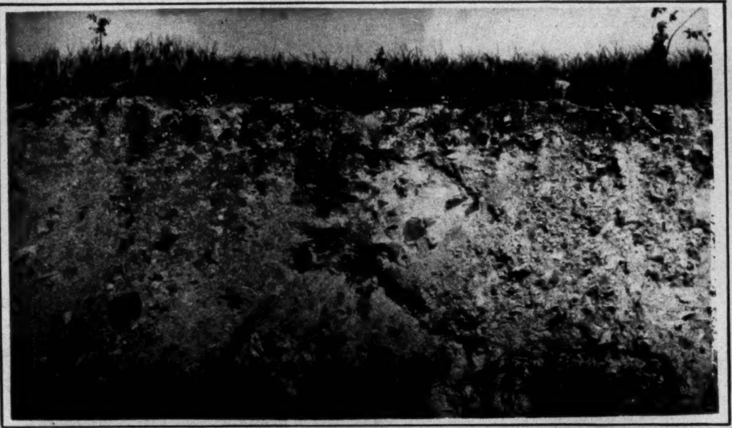

Fig. 5--Mixed breccia in west wall of railroad cut north of Central Senado, showing heterogeneity; small lens of waterlaid debris dipping steeply southward near center of view; height of exposure about 12 feet

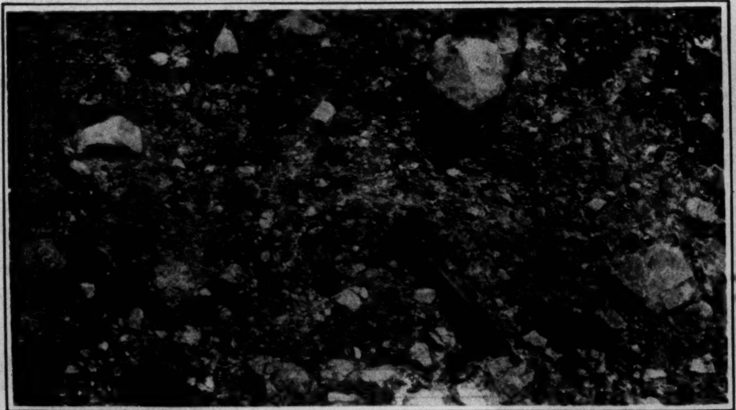

Fig. 6--Close-up of breccia unit similar to that shown in Figure 5, showing angularity of fragments and lack of sorting

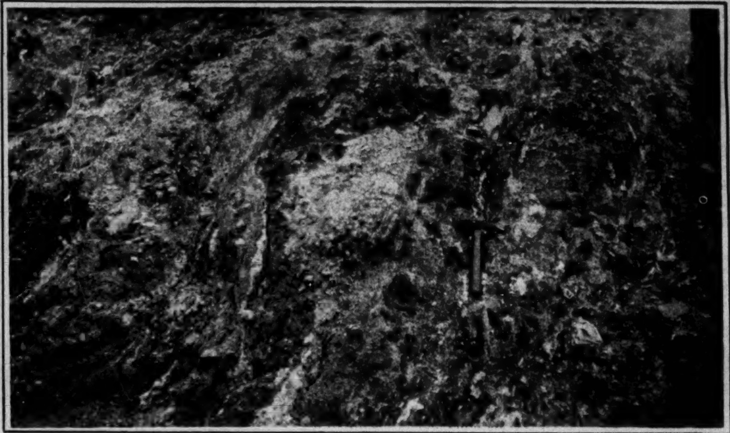

Fig. 7--Breccia resembling fault gouge, in which limestone fragments have been sheared out into lenses and streaks in serpentinous matrix; west wall of railroad cut north of Central Senado, Camagüey

A few thin lenses of waterlaid sandy to gravelly material are interlayered with the breccia. These sediments are in general analogous to the water-worked debris commonly found in morainal deposits; they grade into and obviously were derived from the underlying breccia, and have been disturbed to various degrees. The lenses range in thickness from a foot or two up to 20 feet, and lie approximately parallel to the stratification in the breccia.

The giant breccia lies along the extension of the Cubitas overthrust and at a corresponding altitude. The rocks composing the breccia include those involved in the thrusting and no others, namely, aptychus and other limestones, various facies of the ultramafic complex, and volcanic tuffs. They are regarded therefore as fault breccias similar to those exposed along the base of the Sierra de Cubitas, though developed on a grander scale. The interlayering of waterlaid debris shows that the breccias were exposed to erosion, presumably along the advancing edge of an erosion thrust, and were then overridden by the upper plate. These breccias have many features in common with the "chaos" described by NOBLE [1941] east of Death Valley, and appear to be similar in origin. Several low hills in the vicinity of the breccia exposures are covered with float derived from the ammonite- and aptychi-bearing limestones and are believed to be held up by large blocks from the lower part of the upper plate.

The dip of the overthrust apparently varies considerably from place to place. At the east end of the Sierra de Cubitas and under the Sierra de Camaján it appears to be horizontal. In the vicinity of Banao, however, the fault must dip more steeply than the surface of the serpentine, whihh slopes gently toward the mountain; it may dip 15° or more northeastward.

Like many overthrusts, the Cubitas fault appears to be arcuate. The front of the upper plate is convex to the south, and the major structures of the district as a whole are parallel to it. The central syncline is concave northward and is believed to have been formed by the forces that caused the overthrusting. Exposures in most of the chromite mines show that the serpentine is highly sheared, and segments of faulted gabbroic dikes indicate that displacements of many feet along shears are common. High-angle shearing is so intense in the serpentine in a zone one to two miles wide along the front of the Sierra de Cubitas that it shows clearly in aerial photographs. Some of the fresher gabbro bodies there have been reduced to mylonite and superficially resemble hornfels. Most of the dikes and irregular masses of gabbroic rock in this belt are oriented parallel to the shear planes, though whether by rotation during shearing or by earlier primary igneous control is not known.

The Cubitas overthrust probably developed in the middle Eocene, for it involves lower and middle Eocene limestones, and upper Eocene limestones lie nearly horizontal only six miles northeast of Central Senado, on the projection of the Sierra de Cubitas. The presence of serpentine sandstone in the fault breccia and as slices along minor thrusts suggests that in places the overthrust followed an unconformity which was in part a surface of marine planation, for such sandstones could have been formed only under marine conditions. Subaerial erosion, even in an area of relatively high relief, would have resulted in oxidation and formation of lateritic products.

The reverse fault in the Rio Máximo and the related faults dip southwest, opposite to the Cubitas overthrust, and presumably they were sheared off by it. Though probably small, they are additional evidence of the intense compression to which the serpentine was subjected. The shearing in the serpentine throughout the Camagüey district therefore is believed to be due to diastrophic movements rather than late-stage magmatic processes.

The structure in the southern part of the district is complicated by two stock-like masses of quartz diorite, one which underlies the city of Camagüey, and another to the southeast, just outside the mapped area. These rocks and related dikes in the serpentine also show the effects of strong deformation.

Holguín district--The geology of the section between Holguín and the north coast is similar to that of the Camagüey district. Rocks known to be older than the serpentine were not found in place, but inclusions of altered diorite and tactite indicate that the original peridotite came up through a crystalline basement. Upper Cretaceous tuffs containing limestone lenses overlie the serpentine, and both they and the serpentine are cut by numerous dikes of uralitic diabase and andesitic to rhyolitic porphyries. The city of Holguín is on a stock of hornblende diorite, dikes of which have chilled margins against the serpentine. Oligocene and Miocene limestones wrap around the district and form picturesque steep-sided knobs and mesas within it.

All the pre-Oligocene rocks have been compressed into a number of east-west folds, and the serpentine is exposed principally along the crests of three main anticlines. Cuts along the Holguín-Gibara road show that the rocks are highly deformed, and in several places serpentine is faulted against tuff. Highly brecciated serpentine that contains blocks of diabase, probably from broken up dikes, is thrust southward over tuffs in a cut 3.5 miles north of Holguín (see Fig. 3B). Aerial photographs show many small domical folds involving serpentine northwest of Holguín and one of them is crossed by a prominent fault that strikes northwest.

Chaotic breccias similar to those near Senado are well exposed in a cut through Loma La Vigía, 16 miles from Holguín on the Gibara road. The cut is about 750 feet long and nearly 40 feet in greatest depth (see Fig. 8). The exposed section differs from that north of Senado in that it shows no tuffs or ultramafic rocks (although a block of serpentine is exposed in the road bed just below the section), and waterlaid debris constitutes a large part of it. The breccia members are composed almost entirely of limestone, some blocks being as much as 20 feet long. Most of the fragments appear to be from Upper Cretaceous limestones, and some contain pieces of large rudistids. A few pieces of shaly limestone and chert were seen in the breccia.

The waterlaid materials range in size from angular gravel to marl, and include basal conglomerates derived from the underlying breccia. Contemporaneous deformation is shown by numerous angular unconformities involving variations in attitude of 45° or more. The beds all dip southward except in a few places where they are steeply overturned to the north, and in general the younger beds to the south dip less steeply than the others. Lensing of the breccias is shown by one member that is nearly 25 feet thick in the west side of the cut, and pinches out on the east side. The blocks near the center of the section (see Figs. 9 and 10) are in the thin edge of this member.

The deposits in Loma La Vigía, like those in Camagüey, appear to have been laid down along the front of a thrust sheet advancing from the north. The overturning of beds toward the north, lower dips in the successively higher beds toward the south, and the north-dipping reverse faults farther south all indicate movements from the north toward the south. Much of the upper plate of the La Vigía thrust appears to have been destroyed by erosion, for the area northeast of the road cut is occupied by a low coastal plain, but limestone hills that extend for several miles to the northwest probably are part of it. Exposures to the south indicate that the cut reveals only part of the section of thrust breccias. The large blocks of brecciated limestone should assist greatly in tracing the breccia zone even where exposures are poor.

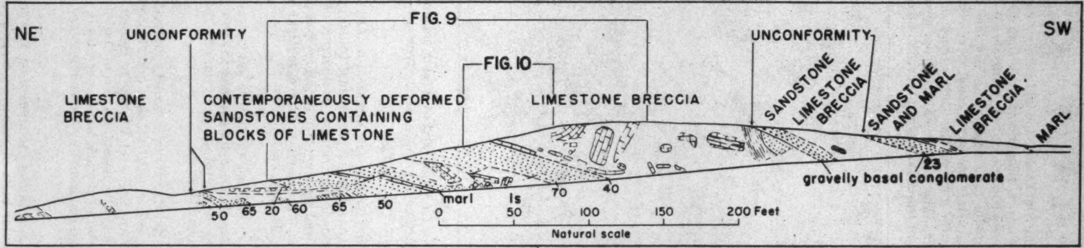
NE
SW
FIG. 9
FIG. 10
UNCONFORMITY
UNCONFORMITY
LIMESTONE BRECCIA
CONTEMPORANEOUSLY DEFORMED SANDSTONES CONTAINING BLOCKS OF LIMESTONE
LIMESTONE BRECCIA
SANDSTONE
LIMESTONE BRECCIA
SANDSTONE AND MARL
LIMESTONE BRECCIA.
MARL
gravelly basal conglomerate
23
marl
ls
70
40
50
65
20
60
65
50
0
50
100
150
200 Feet
Natural scale

Fig. 8--Section in road cut through Loma La Vigía, 16 miles north of Holguín, Oriente Province, Cuba; figures show true dip of beds; covered areas blank

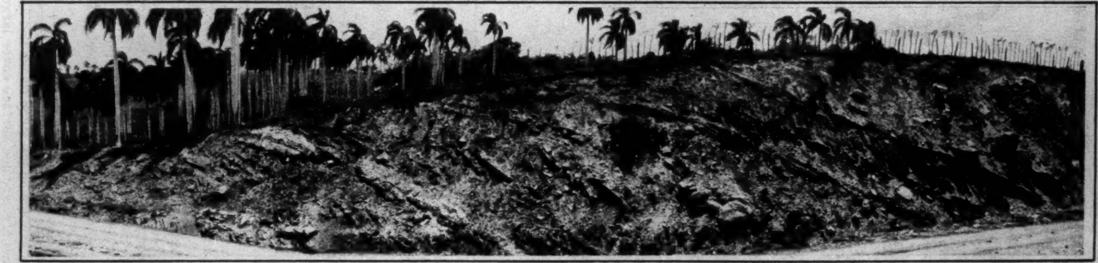

Fig. 9--Interlayed breccia and waterlaid material in Loma La Vigía portion of cut shown is indicated in Figure 8, above

Zone of domical uplifts

The zone of domical uplifts begins on the west with the Sierra de Nipe and extends eastward to within a few miles of Cape Maisí at the eastern tip of Cuba, a distance of more than 100 miles. The main structural units in the zone are: (1) The Sierra de Nipe dome; (2) the Sierra del Cristal dome; and (3) the Cuchillas uplift, a complex unit that includes the Cuchillas de Toar and Sierra de Purial. The zone averages about 25 miles in width and parallels the north coast from Nipe Bay eastward. The Cauto trough and Guantánamo basin adjoin the zone on the south except along the Sierra de Purial, which slopes off into the Bartlett Trough. The mountains rise from near sea level to altitudes of 2000 to 4000 feet and comprise some of the most rugged terrain in Cuba.

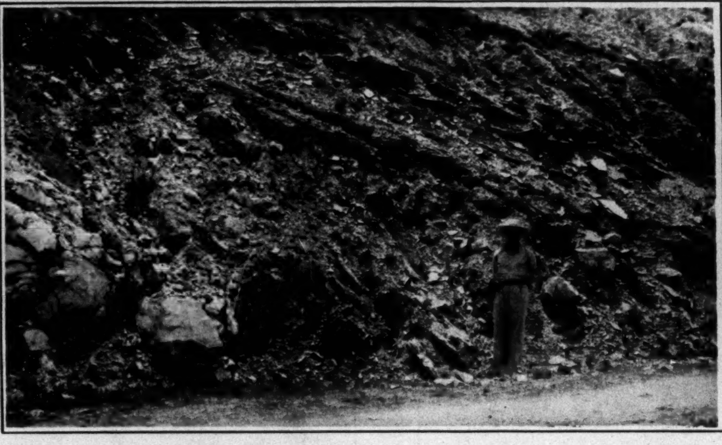

Fig. 10--Close-up showing character of breccia in Loma La Vigía, and overlying thin-bedded calcareous sandstones; note block of thin-bedded cherty shale; area covered by photo indicated in Figure 8

As shown in Figure 1, the Sierra de Nipe and Sierra del Cristal are elliptical domes with cores of serpentine flanked by younger sedimentary rocks, and separated by a synclinal fold along the Río Mayarí. Steeply folded Upper Cretaceous and Eocene beds that contain boulders of serpentine and diorite flank these domes on the south and southwest, and are overlain by upper Eocene and Oligocene beds that extend far up on all sides of the domes. The older beds are vertical in places, and the steepest dips seen in the Oligocene beds are about 20 degrees.

The Cuchillas uplift is somewhat longer than the Sierra de Nipe and Sierra del Cristal combined, and is much less well known than they. The Cuchillas de Toar lie north of the Río Toa and are made up for the most part of serpentine, but the Sierra de Purial, south of the Río Toa, consists largely of pre-serpentine metamorphic rocks of unknown age.

The Cuchillas de Toar are separated from the Sierra del Cristal by a broad synclinal lowland drained by the Río Sagua de Tánamo. The serpentine core of the uplift extends practically to the coast from a point about 15 miles east of the mouth of the Río Sagua de Tánamo to Baracoa, for the strip of Tertiary beds along the coast is very narrow and discontinuous. From Baracoa southward the Tertiary beds dip eastward away from, and wrap around, the eastern tip of the Sierra de Purial. The Cuchillas uplift as a whole is flanked on the southwest by the sedimentary rocks that form the Guantánamo basin.

The present relief of this mountainous belt is due to uplift along the axes of earlier folding, accentuated by erosion on the steep flanks and along irregular belts of relatively weak rocks. Remnants of an extensive erosion surface cover large areas in the higher parts of all the sierra. This surface is best preserved in the vicinity of Moa, on the north slope of the Cuchillas uplift, and is referred to as the Moa surface. The lateritic iron-ores of eastern Cuba, including the famous Mayarí and Moa fields, are on this or a closely related surface. Near Moa the laterite-covered surface rises southward at an angle of about five degrees from sea level to more than 2000 feet, and the parts above the 500-foot contour are being rapidly dissected by stream erosion. The laterite extends seaward under Moa Bay, where the low dip has permitted the formation of a barrier reef. A few miles north of Baracoa the flank of the uplift, which appears to dip seaward about 15 degrees, has been stripped of laterite, and deep water is close to the shore. The Cuchillas uplift, therefore, extends below sea level, and the coastline from Baracoa westward for a distance of about 40 miles is essentially the sea-level contour on the Moa surface. Although erosion has stripped the laterite from the steeper parts of the Sierra de Nipe dome and accentuated the plateau-like aspects of the summit areas, the original domical form of the sierra is shown by the longitudinal profiles of the main ridges. The relief directly caused by doming is therefore on the order of 2000 to 3000 feet. The Moa surface cuts across all the rocks, although best preserved on the serpentine, and is believed to have been formed during Pliocene time, when similar surfaces were being developed in the Sierra Maestra [TABER, 1934]. It has been argued that the laterite might have been formed where it now is, rather than on a surface of low relief near sea level, and that the uplands accordingly do not necessarily indicate uplift of the magnitude and character indicated. Everywhere except on the lower slopes around Moa the streams are rapidly destroying the laterite-covered surface by cutting deep valleys into it. The intricate and deep dissection, with development of steep knife-like ridges (whence the name "Cuchillas"), that characterizes the present cycle is regarded by the authors as precluding formation of extensive laterite-covered surfaces except near sea level under climatic conditions similar to those of the present.

General relations

Although the structural zones have been described as distinct, with individual characteristics, they apparently were formed by the same crustal forces, as they have certain features in common. The principal differences appear to be of degree rather than kind, and indicate decreasing intensity of deformation southward. Small domical folds are as characteristic of the Holguín district as the reverse faults are, and there are many domes in the sedimentary rocks south of the Sierra de Nipe. The structure of the Sagua de Tánamo district in the northern edge of the zone of domes is very complex, and thrust faults are known to be present. On the road to the Talión mine, 2 1/2 miles west of Sagua de Tánamo, serpentine overlies tuffs on a nearly flat shear, and an erosional contact between the tuffs and serpentine is well exposed 100 yards nearer the mine. There is, therefore, no apparent definite boundary between the zone of thrust faults and the zone of domes.

The major structural axes in the Camagüey and Holguín districts obviously do not line up (see Fig. 1), and they appear more likely to be en echelon. The extensive area of younger Tertiary rocks west of the Camagüey district precludes close correlation with the Santa Clara region, but RUTTEN [1936, p. 28] indicates that the same general situation holds there also, for he describes a southern zone of gentle folding and a northern zone of tight folding and overthrusting. It is not known whether the main structural axes parallel the length of the island or cross it diagonally. If the thrusting is related to the development of a tectogene off the north coast of Cuba as postulated by HESS [1938], it would appear that the tectogene was formed mainly during the late Cretaceous and early Tertiary. If, however, the intrusion of the ultramafic rocks marked the first stage in its development, the tectogene must have been initiated in early Cretaceous time, and perhaps earlier.

The influence of the peridotite on the deformation is not clear. Very little is known about the form and extent of the peridotite masses in either the Camagüey or Oriente districts, as most of the margins are concealed by younger formations. The peridotites in the Oriente district appear to be either batholiths or very thick sheets, for although they formed topographic highs during much of late Cretaceous and Tertiary time, and must have been deeply eroded, no evidence of their floors has been found. The ultramafic complex in Camagüey Province shows some of the features of a lopolith and may be a relatively thin sheet [FLINT, DE ALBEAR and GUILD, in press]. The Camagüey complex and the serpentines in Holguín apparently failed to act as buttresses, and were folded and faulted as if they were thick sedimentary formations. The peridoties in the zone of domes retain most of their original structures, and although largely serpentinized, do not show the effects of strong shearing. Intense local deformation in the older beds around the edges of the domes would seem to indicate that the peridotites originally were competent and formed buttresses of a sort. The composition of the boulders in the Cretaceous and Eocene beds, however, indicates that serpentinization was far advanced early in the deformational history of the region, and it seems questionable whether serpentine, even in very large masses, would form effective buttresses. The serpentine in the domes therefore is presumed to have escaped internal deformation by virtue of weakness of the deforming forces rather than its own strength.

The late Tertiary deformation increases in magnitude from northwest to southeast, and is strongest in the Cuchillas uplift. The Camagüey district affords, at most, evidence of broad warping with a relief about equal to the height of Mesa San Felipe, or 200 to 300 feet. The Nipe dome stands about 2000 feet above the surrounding plains, and the Cuchillas uplift has a probable total relief of considerably more than 3000 feet. The amount of deformation appears to be roughly in inverse proportion to the distance from the Bartlett Trough, the nearer the trough, the more intense the deformation.

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PROGRESS REPORT OF THE JESUIT SEISMOLOGICAL ASSOCIATION FOR THE YEARS 1945 AND 1946

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The years 1945 and 1946, including as they do the transition from wartime restriction to peacetime freedom, deserve more than usual attention.

During the war years the tripartite arrangement between Science Service, the United States Coast and Geodetic Survey and Geodetic Survey, and the Jesuit Seismological Association was maintained; but the sources of information were so diminished in number and the personnel and facilities were so greatly curtailed that epicenters of earthquakes publicly announced were necessarily fewer in number and the information contained in the Preliminary Bulletin of the Central Station at Saint Louis was much less extensive.

Nevertheless during the year 1945 the following epicenters were determined.

Table 1--Summary of "Preliminary Bulletins on Epicenters, 1945"

Bull. No.	Date	Epicenter		Time (U. T.)	Depth	Remarks
		Latitude	Longitude			
	1945	°	°	h m s	km	
1	Jan. 1	72.3 N	70.0 W	01 20 46	. . .	
2	Jan. 12	35.5 N	135.0 E	18 38 25	. . .	
3	Jan. 12	15.5 N	93.5 W	21 59 31	100	
4	Feb. 10	42.3 N	140.0 E	04 58 04	120 ±	
5	Feb. 26	21.0 N	144.0 E	22 14 30	. . .	
6	Feb. 18	8.0 N	82.5 W	6 46 30	. . .	
6	Feb. 18	43.0 N	147.0 E	10 08 22	. . .	
7	Mar. 11	26.0 N	141.5 E	21 37 57	100 ±	
8	Mar. 17	6.2 N	78.1 W	23 57 57	. . .	
9	Mar. 18	44.0 N	33.0 W	23 18 16	. . .	
10	Apr. 15	54.8 N	162.4 E	02 35 29	150 ±	
11	Apr. 15	21.3 N	107.2 W	19 50 36	. . .	
12	Apr. 21	18.0 N	100.7 W	17 14 19	100	
13	Apr. 19	42.5 S	179.5 E	13 03 33	100	
14	May 19	16.1 N	98.2 W	07 55 56	100 ±	
15	May 19	40.2 N	126.2 W	15 07 03	. . .	
16	May 9	8.0 S	123.5 E	03 31 15	550 ±	
16	May 10	13.5 S	76.0 W	17 53 30	50	Lima, Peru
16	May 13	24.0 N	109.0 W	20 27 44	. . .	
17	June 3	8.7 N	82.0 W	13 05 39	80 ±	Chiriqui, Panama
18	June 20	47.8 N	152.9 E	01 23 56	. . .	
18	June 20	47.8 N	152.9 E	17 35 18	. . .	
19	June 22	45.2 N	146.6 E	09 18 48	100 ±	
20	June 27	27.3 N	111.1 W	13 08 25	. . .	Santa Rosalia, Lower California
20	June 27	27.3 N	111.1 W	18 08 09	. . .	
21	June 30	17.0 N	115.9 W	05 31 23	. . .	
22	June 1	50.1 N	170.9 W	15 13 49	200 ±	
22	June 1	7.0 N	35.0 W	22 24 13	. . .	
22	June 6	57.5 N	28.7 W	07 00 12	. . .	
22	June 22	33.0 N	75.0 W	18 01 00	. . .	
22	June 24	34.0 S	71.5 W	19 58 07	100	
23	July 9	4.3 N	77.2 W	16 42 17	. . .	Western Colombia
24	July 15	15.5 N	143.5 E	05 35 07	150	
25	July 26	34.4 N	81.4 W	10 32 17	. . .	S. C., N. C., Ga., Tenn.

Table 1--Summary of "Preliminary Bulletins on Epicenters, 1945" (Continued)

Bull. No.	Date	Epicenter		Time (U. T.)	Depth	Remarks
		Latitude	Longitude			
	1945	°	°	h m s	km	
26	July 2	20.2 N	109.5 W	08 31 04	. . .	
26	July 11	59.0 N	150.4 W	00 30 50	100	
26	July 17	13.5 N	92.0 W	06 46 58	. . .	
27	Aug. 2	54.3 N	132.9 W	20 44 45	. . .	
28	Aug. 3	6.1 N	82.2 W	04 11 33	. . .	
28	Aug. 3	6.1 N	82.2 W	06 34 44	. . .	
29	Aug. 10	15.5 N	89.0 W	11 20 19	. . .	
30	Aug. 11	6.0 N	82.0 W	00 33 44	. . .	
31	Aug. 15	33.1 N	116.1 W	17 56 4	. . .	According to Pasadena
32	Aug. 29	15.5 S	169.2 E	10 22 43	. . .	
33	Aug. 27	26.0 N	142.5 E	07 34 47	. . .	
34	Sep. 1	45.2 S	166.7 E	22 44 17	. . .	
35	Sep. 2	33.6 N	30.0 E	11 54 01	100	
36	Sep. 5	5.0 S	154.0 E	21 48 51	. . .	
37	Sep. 9	16.7 S	167.1 E	4 02 50	50 ±	
38	Sep. 13	32.9 S	70.3 W	11 17 20	100	Santiago, Chile
39	Sep. 14	7.6 N	39.3 W	02 02 39	90	
40	Sep. 26	19.5 N	64.5 W	14 27 01	. . .	
41	Sep. 28	41.5 N	126.2 W	22 24 08	. . .	
42	Sep. 7	45.8 N	27.6 E	15 48 28	100	
42	Sep. 19	45.5 N	145.7 E	12 28 14	. . .	
42	Sep. 22	2.8 S	146.5 E	09 09 49	. . .	
42	Sep. 23	19.5 N	104.8 W	17 20 55	. . .	
43	Oct. 7	12.9 N	89.9 W	13 23 34	. . .	
44	Oct. 9	44.0 N	146.8 E	14 36 43	100 ±	
45	Oct. 11	17.6 N	97.5 W	16 52 54	50 ±	
46	Oct. 15	59.0 N	139.2 W	08 01 12	. . .	Sitka, Alaska
47	Oct. 25	57.2 N	163.6 E	14 58 50	60 ±	
48	Oct. 27	15.9 N	91.4 W	11 24 43	200 +	
49	Oct. 29	51.1 N	130.0 W	10 54 27	50 ±	
50	Oct. 14	15.4 S	172.7 W	04 07 12	. . .	
50	Oct. 16	2.0 S	123.0 E	16 03 08	100 ±	
50	Oct. 20	48.9 N	128.5 W	00 32 55	. . .	
51	Nov. 3	59.0 N	150.4 W	22 09 03	. . .	
52	Nov. 8	80.9 N	23.8 W	09 05 41	. . .	
53	Nov. 8	80.9 N	23.8 W	10 02 52	. . .	
54	Nov. 16	58.2 N	136.2 W	18 02 21	. . .	Sitka, Alaska
55	Nov. 26	22.4 S	179.1 W	05 13 10	550	
56	Nov. 27	24.9 N	61.0 E	21 57 00	. . .	India
58	Dec. 8	6.0 S	151.0 E	01 04 00	. . .	
59	Dec. 9	14.4 N	92.1 W	20 45 52	. . .	
60	Dec. 20	7.6 N	129.8 E	03 59 26	. . .	
61	Dec. 23	9.5 N	62.5 W	08 10 16	100-200	
62	Dec. 25	50.4 N	172.9 E	01 26 01	200	
63	Dec. 27	6.0 S	151.0 E	04 41 05	. . .	
64	Dec. 28	6.0 S	151.0 E	17 48 52	. . .	
65	Dec. 14	4.5 S	79.0 W	17 26 40	150 ±	

In 1946 the number of clusters of neighboring epicenters was noticeably greater than in 1945. In each of the years there was at least one earthquake whose focus was deeper than 500 km.

Since the close of the War, many improvements have been made in the equipment of member stations. At Loyola University in New Orleans and at John Carroll University in Cleveland, respectively, two long-period horizontal component Sprengnether seismographs and a short-period vertical Sprengnether seismograph, together with a triple drum designed and built by the same company, have been installed. Two long-period horizontal seismographs and a triple drum are under construction by the Sprengnether Instrument Company for Canisius College in Buffalo where

Table 2--Summary of "Preliminary Bulletins on Epicenters, 1946"

Bull. No.	Date	Epicenter		Time (U. T.)			Depth	Remarks
		Latitude	Longitude					
	1946	°	°	h	m	s		
1	Jan. 5	14.9 N	91.5 W	01	15	13	250 ±	
2	Jan. 5	15.9 S	167.0 E	20	57	32	100	
3	Jan. 12	59.4 N	148.2 W	20	25	39	. . .	Felt at Anchorage and Cordova, Alaska
4	Jan. 4	10.0 N	84.0 W	19	43	47	50	
4	Jan. 11	43.5 N	130.0 E	01	33	30	600	
4	Jan. 11	18.0 N	93.5 W	18	41	33	. . .	
5	Feb. 15	47.3 N	122.7 W	03	17	49	. . .	
6	Feb. 4	52.2 N	175.5 W	03	44	58	150	
6	Feb. 12	36.0 N	5.0 E	02	43	30	. . .	
7	Mar. 15	35.73N	118.04W	13	49	36	. . .	According to Richter, (Pasadena)
8	Mar. 29	2.8 N	75.8 W	07	17	35	. . .	Felt in Popoyan, Colombia
8	Mar. 29	2.0 S	80.0 W	07	26	12	100	Felt in Ecquador
9	Mar. 12	35.8 S	105.5 W	00	02	00	100	
9	Mar. 12	32.0 N	53.0 E	02	21	50	. . .	
9	Mar. 25	19.0 N	74.7 W	08	47	40	. . .	
9	Mar. 25	15.5 N	93.2 W	22	16	47	. . .	
10	Apr. 1	53.0 N	162.7 W	12	29	04	50 ±	
11	Apr. 11	1.1 S	14.9 W	01	52	32	. . .	
12	Apr. 23	49.8 S	139.0 E	04	56	05	. . .	
13	Apr. 23	16.2 S	173.6 W	10	39	58	. . .	
12.	Apr. 26	49.4 N	147.7 E	08	09	25	600 ±	
12	Apr. 29	19.6 N	70.5 W	01	31	33	. . .	
13	May 3	7.0 S	155.0 E	22	23	50	. . .	Felt in Rabaul Area, New Britain
14	May 8	0.3 N	98.3 E	05	20	18	. . .	
15	May 9	23.1 N	108.1 W	23	34	29	. . .	
16	May 15	16.0 N	96.2 W	22	10	40	50 ±	
16	May 15	16.0 N	96.2 W	22	24	22	. . .	Aftershock
17	May 21	15.3 N	60.5 W	09	16	44	. . .	Deep (?)
18	May 12	42.1 N	28.3 W	13	20	20	. . .	
18	May 16	9 S	158 E	05	25	.3	. . .	
18	May 19	55.0 N	165.5 E	00	31	27	80	
18	May 30	46.1 N	7.5 E	03	41	18	. . .	
18	May 31	39.1 N	41.1 E	03	12	43	. . .	
19	June 7	16.7 N	94.6 W	04	13	18	100	
20	June 23	50.0 N	125.0 W	17	13	19	. . .	
21	June 24	14.9 N	89.7 W	15	48	16	200 ±	
22	June 26	14.3 N	91.3 W	07	53	50	200 ±	
23	June 6	1 N	20 W	10	38	05	. . .	
23	June 9	53.0 N	161.0 W	06	56	23	. . .	
23	June 12	12.1 N	143.4 E	16	08	21	. . .	
23	June 15	3.9 S	127.9 E	18	29	22	. . .	
23	June 26	42.9 S	171.6 E	12	34	42	. . .	
23	June 30	17.7 N	94.6 W	04	59	35	200 ±	
24	July 1	64.0 N	149.0 W	02	52	24	. . .	
25	July 11	16.7 N	94.6 W	04	46	30	50	
26	July 18	50.0 N	130.0 W	06	07	02	50 ±	
26	July 18	50.0 N	130.0 W	07	16	36	50 ±	
27	July 25	50.6 N	177.3 W	16	42	24	50 ±	
28	July 26	19.8 S	70.9 W	06	44	53	80 ±	
29	July 9	26.3 S	171.9 W	01	08	12	. . .	
29	July 9	19.2 S	169.0 E	13	13	50	150-200	
29	July 12	52 N	170 W	21	56	23	100	
30	Aug. 2	25.5 S	71.1 W	19	19	01	80 ±	
31	Aug. 4	19.2 N	68.9 W	17	51	07	. . .	
32	Aug. 8	19.2 N	68.9 W	13	28	27	. . .	
33	Aug. 11	8.4 S	155.9 E	01	54	26	. . .	
34	Aug. 21	19.2 N	68.9 W	19	17	43	50 ±	
35	Aug. 28	27.0 S	63.5 W	22	28	21	550-600	

Table 2--Summary of "Preliminary Bulletins on Epicenters, 1946" (Concluded)

Bull. No.	Date	Epicenter		Time (U. T.)	Depth	Remarks
		Latitude	Longitude			
	1946	°	°	h m s	km	
36	Aug. 15	22.3 S	171.5 E	15 24 02	. . .	
37	Sep. 12	23.0 N	92.0 E	15 17 17	. . .	
38	Sep. 13	52.8 N	160.0 E	18 59 17	. . .	Deep (?)
39	Sep. 18	16.0 N	102.0 W	02 09 09	. . .	
40	Sep. 23	4.2 S	148.2 E	23 30 04	. . .	
41	Sep. 25	19.8 N	70.0 W	10 05 42	. . .	Deep (?)
42	Sep. 29	4.8 S	152.8 E	03 01 55	. . .	
43	Sep. 30	12.6 S	75.8 W	00 59 51	100 ±	
44	Sep. 2	17.5 N	95 W	21 51 58	100 ±	
44	Sep. 26	25.6 S	178 E	10 53 16	600	
44	Sep. 30	38.5 S	17.0 W	11 29 20	. . .	
45	Oct. 2	54.0 N	159.7 E	04 46 22	. . .	Deep (?)
45	Oct. 2	54.0 N	159.7 E	06 43 30	. . .	
46	Oct. 4	19.2 N	168.9 W	14 45 35	50 ±	
47	Oct. 22	22.0 S	178.0 E	10 00 41	250	
48	Oct. 30	53.7 N	163.3 W	07 47 44	50 ±	
49	Oct. 14	30.7 S	178.2 W	04 44 45	. . .	
49	Oct. 25	53.5 N	159.8 E	21 50 23	150 ±	
49	Oct. 26	60.6 S	37.0 W	00 21 11	. . .	
50	Nov. 1	51.0 N	173.2 W	11 14 30	. . .	
51	Nov. 2	41.3 N	71.2 E	18 28 39	100 ±	
52	Nov. 3	0.0 N	17.0 W	19 32 40	. . .	
53	Nov. 4	36.2 N	57.1 E	21 47 30	. . .	
54	Nov. 10	7.8 S	77.8 W	17 43 00	. . .	
55	Nov. 12	53.0 N	163.5 W	05 56 22	. . .	
56	Nov. 12	20.2 S	173.5 W	17 28 43	. . .	
57	Nov. 14	19.2 N	68.9 W	11 34 45	. . .	
58	Nov. 28	18.1 S	175.0 W	15 51 36	300 ±	
59	. . .	. . .	. . .	. . . . .	. . .	
59	Dec. 20	33.2 N	135.6 E	19 19 08	. . .	
60	Dec. 21	46.1 N	149.6 E	10 19 01	. . .	
61	Dec. 28	19.2 N	68.9 W	00 58 07	. . .	
62	Dec. 18	55.3 N	151.4 W	00 24 52	. . .	
62	Dec. 19	25.1 N	123.9 E	02 57 24	100 ±	
62	Dec. 21	42.7 N	148.1 E	19 48 41	. . .	
62	Dec. 25	51 N	180 E	11 13 14	100 ±	

a Galitzin-Wilip vertical component and an 80 kg Wiechert horizontal have been in operation for many years.

At Regis College in Denver, two of the older Macelwane-Sprengnether seismographs originally used for research on microseisms by Father Ramirez were placed on loan from St. Louis University as were also two Galitzin-Masing recording drums.

At Mount Saint Michael's College of Gonzaga University there have been installed two long-period Wood-Anderson seismographs on loan to the Jesuit Seismological Association from the Department of Geology of the University of Wisconsin. This arrangement was made largely through the kind offices of L. B. Slichter.

Funds were gathered by the late William Kane for new Sprengnether seismographs to be placed at Loyola University in Chicago where an 80 kg Wiechert has been in operation since 1912.

Anthony J. Westland has installed a Wood-Anderson seismograph on loan from Xavier University, Cincinnati, at Loretto Academy, El Paso, Texas.

J. J. Lynch of Fordham University has placed a Sprengnether seismograph in operation in the region of the Dominican Republic that was affected by the great earthquake of August 4, 1946.

He has also placed a Sprengnether seismograph in the Fordham Station. New stations with Sprengnether equipment are projected for the University of San Francisco and for LeMoyne College in Syracuse.

The McComb-Romberg seismographs loaned by the United States Coast and Geodetic Survey are in continuous operation at Spring Hill College near Mobile, Alabama, under the direction of A. J. Eisele.

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Transactions, American Geophysical Union Volume 28, Number 6 December 1947

REPORT OF THE SUBCOMMITTEE ON SEDIMENT TERMINOLOGY

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This Subcommittee was organized in November 1941. It first selected the areas in which the terminology of sediments was confused and needed clarification, and drew up preliminary definitions to serve as a basis of discussion. These definitions were then distributed as widely as possible among the persons in this country who are active in the sediment field, and their views were requested. Their replies contained many valuable suggestions. The comments on each definition were assembled and the preliminary definitions were modified in the light of these views. In cases where there were distinct differences of opinion, alternate definitions were prepared and voted upon by the Subcommittee. On the majority of items adopted, the vote of the Subcommittee was unanimous, or nearly so, but on several there was considerable difference of opinion.

It was recognized to be very important that the definitions chosen should be as nearly as possible satisfactory to all those engaged in the various branches of this field such as geology, fluid mechanics, sediment measurement in streams and what might be called "sediment engineering," and considerable study was given to the accomplishment of this result. It was also recognized that the recommendation of great changes in the cutomary terminology would not be accepted by workers in the field, and therefore would not produce the desired result. It is believed that the terminology obtained is the best, considered from all viewpoints, which will be generally adopted at the present time. As sediment science develops it may be necessary to review this subject again, but should this be the case, a new committee should be appointed.

If this report is acceptable, since the work for which this Subcommittee was organized will have been accomplished, as far as it is practicable to do so at the present time, it is suggested that this Subcommittee be discharged.

The following paragraphs give the terminology recommended by this Subcommittee.

General term for material--The generic term for material in this field should be "sediment." It is defined in the New Standard Dictionary as follows: "Fragmental material transported by, suspended in, or deposited by water or air, or accumulated in beds by other natural agents; any detrital accumulation, such as loess." Ordinarily this does not include ice or organic material floating on the surface.

Definitions of the various divisions of material being transported--The following definitions are recommended.

Contact load is the material rolled or slid along the bed in substantially continuous contact with the bed.

Saltation load is the material bouncing along the bed, or moved, directly or indirectly, by the impact of the bouncing particles.

Suspended load can be used for either (1) the material moving in suspension in a fluid, being kept up by the upward components of the turbulent currents or by colloidal suspension, or (2) the material collected in or computed from samples collected with a suspended load sampler. (A suspended load sampler is a sampler which attempts to secure a sample of the water with its sediment load without separating the sediment from the water.) Where it is necessary to distinguish between the two meanings given above, the first one may be called the "true suspended load."

Bed load may be used to designate either coarse material moving on or near the bed, or material collected in or computed from samples collected in a bed load sampler or trap.

Bed-material load is part of the sediment load of a stream which is composed of particle sizes found in appreciable quantities in the shifting portions of the stream bed.

Wash load is that part of the sediment load of a stream which is composed of particle sizes smaller than those found in appreciable quantities in the shifting portions of the stream bed.

A term for the amount of material moved in a unit of time--The term for amount of material moved in unit time should be "discharge." Where this might lead to confusion with water discharge, it should be qualified as for example, sediment discharge or saltation load discharge.

A grade scale of size terms--The scales of sizes shown in Tables 1 and 2 are recommended.

Table 1--Scale of large sizes in metric and English units

Class name	Metric unit	English unit
	mm	in
Very large boulders	4096-2048	160-80
Large boulders	2048-1024	80-40
Medium boulders	1024-512	40-20
Small boulders	512-256	20-10
Large cobbles	256-128	10-5
Small cobbles	128-64	5-2.5
Very coarse gravel	64-32	2.5-1.3
Coarse gravel	32-16	1.3-0.6
Medium gravel	16-8	0.6-0.3
Fine gravel	8-4	0.3-0.16
Very fine gravel	4-2	0.16-0.08

Table 2--Scale of small sizes

Class name	Metric units		
	mm	mm	microns
Very coarse sand	2-1	2.000-1.000	2000-1000
Coarse sand	1-1/1	1.000-0.500	1000-500
Medium sand	1/2-1/4	0.500-0.250	500-250
Fine sand	1/4-1/8	0.250-0.125	250-125
Very fine sand	1/8-1/16	0.125-0.062	125-62
Coarse silt	1/16-1/32	0.062-0.031	62-31
Medium silt	1/32-1/64	0.031-0.016	31-16
Fine silt	1/64-1/128	0.016-0.008	16-8
Very fine silt	1/128-1/256	0.008-0.004	8-4
Coarse clay size	1/256-1/512	0.004-0.0020	4-2
Medium clay size	1/512-1/1024	0.0020-0.0010	2-1
Fine clay size	1/1024-1/2048	0.0010-0.0005	1-0.5
Very fine clay size	1/2048-1/4096	0.0005-0.00024	0.5-0.24

A standardization of the terms for the diameter of a particle--The following terms for diameter of particles are recommended.

Sieve diameter is the size of sieve opening through which the given particle will just pass.

Nominal diameter is the diameter of a sphere of the same volume as the given particle.

Sedimentation diamter is the diameter of a sphere of the same specific gravity and the same terminal uniform settling velocity as the given particle in the same sedimentation fluid.

The basis for computing the concentration of suspended material--The recommended method for determining the concentration of suspended sediment is, weight of dried sediment divided by weight of sample, including weight of solids, water, and dissolved material. Since for sediment concentrations less than one per cent the results computed by the following two methods differ less than one per cent from the results obtained by the recommended method, for such concentrations the use of the following methods is permissible: (1) Weight of the dried sediment divided by weight of distilled water with a volume equal to that of the sample or (2) weight of the dried sediment divided by weight of the water in the sample, including the dissolved material.

A standardization of units used in recording concentration of suspended sediment--The ratio used in expressing the concentration of suspended sediment should be given in either parts per million (ppm) or per cent.

Definition of other terms--The following definitions are recommended for other terms.

A sand-wave is a ridge on the bed of a stream formed by the movement of the bed matieral, which is usually approximately normal to the direction of flow, and has a shape somewhat resembling a water wave.

A dune is a sand wave of approximately triangular cross section (in a vertical plane in the direction of flow) with gentle upstream slope and steep downstream slope, which travels downstream by the movement of the sediment up the upstream slope the the deposition of it on the downstream slope.

An anti-dune is a sand wave, indicated on the water surface by a regular undulating wave, in appearance like that formed behind a stern wheel steamboat. These ridges move, usually upstream. The surface waves become gradually steeper on their upstream sides until they break like surf and disappear. These waves are usually in series and often reform after disappearing.

Classification of sediments covering a wide range of sizes--A sediment covering a wide range of sizes may be classified in one of the major size classes previously discussed such as clay, silt, or sand, if its geometric mean diameter lies in that range. If the geometric mean is unknown, the median diameter may be used instead.

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DISCUSSION OF "SHEAR PATTERNS OF THE EARTH'S CRUST" by F. A. VENING MEINESZ

[Trans., v. 28, pp. 1-61, 1947]

R. A. Sonder (Oberrieden, Switzerland, May 18, 1947)--Abstract--The crustal shear pattern proves the existence of a rigid, elastic crust of considerable strength in which distortional forces of importance must have occured. As no handy terms exists for these distortional geotectonic forces, the writer proposes to use the expression "regmagenic forces." Such forces can be created in the crust by a polar drift of the crust over the core, by great fluctuations of the elastic compression in the presence of sensible elastic anisotropies or by unequal tangential stresses (orogenic forces). The writer agrees with Vening Meinesz that polar drifts played a part in the making of the regmatic shear pattern of the crust. He does not think however that this was the only cause and attributes great importance to the other two mentioned reactions. The writer does not believe in the existence of subcrustal currents sufficient to create crustal tectonics and rejects also the idea of such currents as source of a polar drifting. Even if they existed, their total drift moment on the whole crust would be inadequate to overcome the strong elastic counterforces within the crust. Polar drifts can be explained in harmony with the mechanical principles admitting the presence of a sensible general elastic compression and additional regmagenic forces in the tangential plane of the crust. This mechanical deduction and the proved polar displacements of the past point out that an Earth contraction stands behind the tectonical unrest. A revision of this old concept on the ground of modern knowledge seems highly promising. The origin of the continents is discussed under such an assumption as well as the regmatic pattern of the Earth's crust. The continents are explained as the scars of the past tectonic surface reductions. Some related problems are discussed, especially the significance of the drowned islands of the Pacific lately described by HESS [see "References" at end of discussion, 1946] as metering cones of the progressing contraction of the Earth of the past.

I have not entered into details as to how the crustal shear pattern manifests itself in the Earth's features as Vening Meinesz' paper contains many facts and details in this respect. The traits are so obvious that no one could deny them. I may mention that in one of my publications later than those cited by the author, I have treated the connected problem of the origin of the continents [SONDER, 1939].

Definition of terms--I have used the expression "lineaments" as used earlier by American authors. Working on a presentation of a geomechanical theory, I came to the conclusion that with the lineaments and other related features we touch a fundamental chapter of geomechanics. The expression "lineament tectonics" however is not very convenient. Lineamental structures are related with jointing phenomena in general. They occur not only as features and results of reactions of the whole crust as a unit but also as the result of local folding of strata which theoretically should be kept apart from jointing affecting the entire crust. Not all joints are related to crustal should be kept apart from jointing affecting the entire crust. Not all joints are related to crustal splitting.

I think the best way to clear the situation is the introduction of a new fundamental term reuniting all those problems which are related with the jointing of the crust as a whole. I suggest that the term "regmageny" (rhema, Greek: cleft, fissure) may be used. Regmagenic forces have created the major or regmatic joint system of the crust. The San Andreas fault in California should therefore be called a regmatic joint. Such joints cutting the crust more or less perpendiculary work as shear planes for horizontal shifting in order to compensate elastic distortions (regmagenic forces) in the horizontal plane of the crust. Regmagenic forces may not only cause lineamental features but may also be responsible for magmatic infiltrations in certain regions [SONDER, 1936]. By introducing the term regmagenic we get a full system of the possible theoretical forces related to the tangential deformation of the Earth's crust according to the scheme shown in Table 1.

The meaning of the regmatic joint pattern--I agree with Vening Meinesz that the existence of the regmatic shear pattern is a strong evidence of a rigid crust reacting elastically to tectonic forces. The strength of this crust must be considerable. If this were not so, the world-wide coordination of the regmatic pattern would be impossible. The regmatic dissection runs across ocean bottoms and continental platforms as well, showing everywhere the existence of a strong, rigid, and

Table 1--Systems of forces causing tangential deformation of the Earth's crust

Reaction	Origin of the forces	Resulting movements
Orogenic	Tangential compression or pressure	Folding, thrusting
Regmagenic	Elastic distortions within the tangential plane by unequal tangential pressures	Horizontal shifting, magmatic infiltrations

splitable body. I concur with Vening Meinesz that this fact proves that the continental drift hypothesis is impossible. The so-called "Atlantic cleft or fissure" which has given rise to Wegener's and Taylor's idea of a continental drift is only an especially visible part of the controlling regmatic order. If we wish to explain such features, we have to consider all facts including the internal fracturing of the Atlantic bottom and the many other features which have been summed up in Vening Meinesz' paper and my previous articles. All these traits apparently express similar tendencies. We cannot declare only the Atlantic homologies as important and use them as an argument in favor of a drift, leaving the other even more weighty evidence aside.

The regmatic features seem at first sight to be rather a mystery. I think, however, these facts, properly considered, form an enlightening chapter of crustal tectonics, which tells us that the Earth's crust is not a shapeless plastic mass as it has been depicted in many treatises of geology. In order to understand geotectonic reactions we must come to define strength and elasticity of the crystalline crust. Only on such a foundation can we calculate the forces required to produce certain tectonic effects, instead of making theories without ever mentioning any physical or mechanical data as the approximate stresses involved.

The problem of polar wandering--It seems convenient to introduce for geomechanical considerations a notion which I will call the "elastic potential" of the Earth's crust. Under elastic potential I understand the sum of all energy which is elastically stored within the crust at a given moment. There may be present an orogenic potential when a tangential stress is present and a regmagenic potential when an elastic distortion in a tangential plane is present. The seismicity of the crust is a vivid expression of the presence and working of the elastic potentials. Such elastic forces can be potentially stored in the crust ready to produce tectonic reactions as soon as a release is possible. Any tectonic reaction must draw the necessary force from an existing elastic potential of the crust and thus diminish the potential. Any force, even induced from the outside, must first appear in form of an elastic potential. Therefore we must know the elastic constants of the crust before we can do any geotectonic reasoning. In convenient round numbers [SONDER, 1939] we can put: Young's modulus of continents, 7000 kg/mm^2; of ocean bottoms, 11500 kg/mm^2; and of the crust, 10,000 kg/mm^2.

It is well known that a displacement of the rotational axis of the Earth in a short time is impossible. In order to explain the polar wanderings suggested by the wandering ice sheets of Pleistocene or Permian times Vening Meinesz as well as others think that the crust must have drifted over the asthenosphere. NÖLKE [1924] has objected to this. As the equator is 67.44 km longer than a meridional circumference, any polar drift must immediately increase the elastic potential of the crust and must be against strong elastic counterforces. If the equator became a meridian it would suffer a linear compression of 0.17 per cent corresponding to a tangential pressure of 1700 kg/cm^2. The new equator would show a corresponding tension or would crack, assuming that before the drift no pressure of tension existed within the crust. It is very difficult indeed to find a cause sufficiently strong enough for such a drift able to overcome the corresponding increase of the elastic potential of the crust.

Even admitting that such a shifting happened and that the strains were as Vening Meinesz has described them, I do not think that a shear pattern could result because the regmagenic strains would not be sufficiently strong to shear the crust. If corresponding shear planes existed from older activity, then of course the regmagenic distortion would lead to regmatic shifting by a revival of motion on these joints. It is therefore difficult to agree with Vening Meinesz that the shear pattern was caused by an earlier polar drift. This conclusion does not exclude that polar drift together with other factors may have had an influence on the working out of the regmatic shear pattern. The question is: How can we explain polar drifting in the past?

As long as the elastic potential of the crust is zero, a drift seems impossible. Conditions become different if universal and uniform tangential compression of a minimum value of 1700 kg/cm^2 is present. Under such conditions a polar drift would increase the elastic stresses in one direction and diminish them in another. Only the regmagenic potential would sensibly increase by the drift. Therefore polar wandering is facilitated by the presence of a general tangential stress of approximately 2000 kg/cm^2. Such a tangential stress requires a contraction of the Earth, as no other process seems able to create such a condition. If a general tangential compression is present sufficiently strong to start folding, two consequences will be felt immediately when the folding begins: (1) The elastic dialation will transport an excess of crustal mass towards the folding belt. By this, the rotational balance of the crust will become disturbed according to the principle of rotational flight from the poles. (2) The irregular folding and regional release of stress will profoundly disturb the elastic balance in the crust, creating regmagenic potentials. High stresses will remain in some directions, in others the strain is relieved. It will become possible for the crust to acquire a lower elastic (regmagenic) potential by a drift over the core.

If crustal tectonics is caused by Earth contraction, polar wanderings are an inevitable consequence of each major folding. As a result, crust will be thrown out of its rotational and elastic balance, and the watering path of the poles will be irregular, dictated by the changing situation of the stresses present in the crust and the tendency of the crust to "fall" by drifting to the lowest possible elastic potential. Ice caps have always appeared on the Earth after greater folding paroxisms due to the relief accentuation by mountain making and its climatic consequences. We know that these ice caps must have covered various parts of the Earth, especially during the Permian glaciations. In Permian times the South Pole appeared in different positions touching the southern ends of the continents, but always in such a way that the North Pole was in the waters of the Pacific or the Atlantic. In order to explain the Permian glaciations apparently greater drifting of the poles must be admitted. No individual continental drift is proved by this fact which would have changed the relative position of the continents.

It is strange that today the regmatic shear pattern is orientated in a symetric position to the rotational ellipsoid, because we might expect it in any position if the poles have wandered in the past. It could be an indication that with the actual position of the regmatic joint net with respect to the rotational ellipsoid, this net serves most effectively to lower the elastic potential. This could mean that the crust tends to regain the actual position when the disturbing causes disappear for similar reasons as expressed by the strain pattern of Vening Meinesz. Another supposition could say that the actual adjustment of regmatic pattern and rotational ellipsoid is purely accidental.

The origin of the continents and the regmatic shear pattern--It seems clear that the continents, their shape, size, and location as well as the regmatic shear features must have come into existence during the long tectonic evolution of the crust. Some crustal features may date back to the time when no entire crust existed. The lunar terrae and mariae suggest that also the solidification of the Earth's crust started with acid scoria fields (terrae), floating on a molten surface. When most of the gases had escaped and the convection currents had sufficiently lowered the whole temperature of the globe, the mariae could freeze forming a basaltic layer. The Earth presented then probably a surface picture similar to the Moon today. One could suppose with Vening Meinesz and UMBGROVE [1946] that the tetrahedral arrangement of continents may have its root in the distribution of the convectional currents which could have placed the scoria fields in such a tetrahedral position. We will see later that also another explanation of this arrangement is possible.

It is difficult to figure out the evolution of the crust without adhering to a definite explanation regarding the cause of tectonic diastrophism. The existence of polar drifts favors the concept of a contraction of the Earth. This well-known theory lost favor when the phenomena of radio-activity showed that a contraction cannot be explained by cooling. This objection against a contraction has however become inapplicable too by the development of modern atomic science. Interatomic structure is such that volume changes of matter may occur for quite different reasons than thermal cooling. Today, it is the task of the geologist and geophysicist to investigate if a contraction of the Earth can explain crustal tectonics. From astronomy there is good evidence that a secular contraction of the Earth exists [MEYERMANN, 1928]. Lack of space prevents outlining here all the arguments which favor a contraction of the Earth. In an earlier paper [SONDER, 1922] I have given an exposition how contraction of the Earth must create a periodic storage and release of elastic energy leading to the fact that history of the Earth will show a cyclical evolution of crustal tectonics. This evolution by geocycles has been plainly confirmed since by newer data of radioactive age determinations [HOLMES, 1933; KUENEN, 1941; and WAHL, 1943]. According to the data compiled by Wahl the geocyclical phenomena can be followed in the past for nearly 2000 million years. This time interval contains 12 or 13 orogenic paroxysms spaced at average intervals of about 165 million years. This is indeed an excellent confirmation of the mechanical consequences of an Earth contraction in the crust according to my earlier investigation of 1922. We may therefore also ask how we can explain the origin of the continents supposing a contraction of the Earth.

Once the total crust was formed, contraction of the Earth started to create tangential pressures. In very early times, the weak crust may have broken nearly continuously. With growing thickness and strength the above-mentioned cyclical folding phenomena must have developed. It may be that very early a shear pattern formed according to the idea of Vening Meinesz, because the weak crust then might drift on a possibly still more elliptical core. It is probable too that the continuous renewal of tectonic activity will have maintained such a pattern permanently as being the most suitable joint arrangement for elastic compensation shifting in a spherical contracting shell. That means that also the contraction phenomena must have contributed to the existing shear pattern.

The folding imposed by the continuous surface contraction will always have concentrated on the weakest spots in the crust. Due to enrichment of radioactive substances in the salic differentiates, it is highly probable that the slag fields could not thicken as quickly as the basic crust of the mariae which solidified later. This must have been one of the main causes that the weak spots of the crust remained always with its most salic parts. The slag fields suffering thereby tectonic thickening and growing higher and higher were exposed to erosion and sedimentation within them and in the neighboring regions. We know that thick sedimentary lenses create weakness in the crust and attract folding and thrusting preferentially in later epochs. In this way we come to the conclusion that the original slag fields, remaining always the weakest part of the crust as a consequence of their constitution and further evolution, have developed into the continents of today.

Our actual continents are the tectonic scars of the past tectonic unrest in the crust. By folding of the superficially salic crust, salic matter has been thickened in a kind of mechanical salification process. Hand in hand with it worked a magmatic salification because basaltic magmatic intrusions worked their way up into the continental blocks during tectonic unrest. They underwent a differentiation in the cooler surroundings which created new salic material. So by a long succession of manifold events the preferred tectonic scars grew out into the actual salic blocks, by a complicated process of tectonic and magmatic salification.

In striking contrast to these blocks, stand the oceanic basins where we have to look for the original surviving crust of the earth. Apart from the well-known regmatic fracture zones, especially visible in the Atlantic ocean [SONDER, 1939], the oceanic crust remained without tectonic unrest representing the strongest section. The original crust has become covered during the secular evolution by thick layers of sediments which will be thickest in the most land bound ocean basins. This explains why the Pacific Ocean is today the deepest of the oceans, followed by the Indian and Atlantic Oceans and so on until we come to smaller units such as the Gulf of Mexico and the Black Sea. If we try to calculate the thickness of sediments from these depths and related factors of isostatic balance, we come to the result that the Pacific may contain near to five km of sediments, the open Atlantic over ten km of sediments and still more land bound basins up to 20 km. Taking in account the known velocity of sedimentation in the ocean basins of today (100,000 to several hundred thousand years per m of sediment) and the known age of the Earth we come to similar sedimentary thicknesses. I think that the so-called salic layers of the oceans, which have been detected by seismic investigations and which also correspond more or less to the thicknesses just mentioned, can be identified with this secular sedimentary layer. Some special features as for instance the big Easter Bank in the Pacific and others may possibly be interpreted as the oldest salic slag fields which did not become incorporated in the later continents.

It is clear that during the long tectonic evolution of the crust, certain mechanical tendencies influenced the shaping, orientation, and distribution of the growing tectonic salification scars, namely the continents. I mention a few.

When the strength of the crust is overcome, the resistance against folding is regionally weakened. This principle will tend to concentrate the disturbances in certain regions as far as possible. This may explain why the continents formed as blocks and that tectonic unrest did not spread at random.

The fact, however, that the surface of a sphere had to be reduced did not allow this tendency to lead to the formation of one big continent. Some folding had always occurred at more distant centers. One tempting mechanical solution is that several continental salification scars had to develop whereby the preferred geometrical solution is a tetrahedral arrangement of the continents over the globe, an arrangement which is obvious and has been discussed many times by geographers.

With the salification of the continents, great differences of elastic properties appeared in the crust as previously outlined. The contraction theory leads to the assumption of a cyclical storage and release of elastic energies [SONDER, 1922] in a considerable amount. JEFFREYS, [1929] expressed similar ideas concerning storage and release of elastic energy, and NÖLKE [1924] described the storage-release principle. Elastic anisotropies cannot work in harmony under such changing pressure conditions without sensible regmagenic distortions. The resulting shear tendencies will be orientated according to the size and shape of continents, that is, according to the recognizable regmatic shear pattern of the Earth. In such a mechanical interconnection we see one of the fundamental causes why the regmatic pattern is orientated according to the form of the continents and vice-versa. To describe all these interconnections, however, separating causes and consequences, is a difficult task. I will try to make clear some of these related reactions.

Once a joint net is established, the possibilities of elastic compensation shifting will have influenced the local pressure distribution and also the orientation of new folding fronts, because local folding is impossible in a rigid body without corresponding shear compensations in the rear. So we see from the seismic line map of Europe that the preferential shear paths of the crust run northwest and northeast. The same is true in a sensible way for the curiously dissected European alpine folding pattern. Folding seems to follow the given regmatic shear pattern to a certain extent. As folding means salification and shaping of the continental platform, there must result continental bodies with definite relations toward the established regmatic pattern.

Where greater continental masses surround an oceanic crust of far higher elastic modulus, as it is the case in the Atlantic Ocean, the growing continental masses on both sides will shape into a well established parallelism. Acquiring such corresponding parallel features, the elastic distortions and overstresses which appear under great pressure fluctuations in elastically anisotropic bodies are easily removed by regmatic shifting. Non-parallelism would create local overstresses which may lead to tectonic salification. As salification means a lower Young's modulus there will subsequently be less cause for overstresses in future pressure fluctuations. So we may understand the principle which has created the curious mutual adaptation of forms along the Atlantic Ocean as well as the shaping of the continents in accordance with the regmatic pattern. The explanation is more complicated than the drift theory but seems to stand on firmer mechanical ground. We cannot expect that the highly complicated product of a tectonic evolution dating back millions of years can be explained by too simplified concepts.

If the continents are the final product of a contraction of the Earth, the surface must have diminished sensibly with time. The oceans must have grown deeper and deeper. In the oceans isolated volcanic cones appeared from time to time, apparently indicating an occasional regmatic split. These cones must have become truncated at the existing water level once the activity died. Below the water level, they were preserved and were drowned deeper and deeper as the age of the Earth increased. Only in more recent times drowning could be prevented by coral growth. Borings on some coral islands such as Funafuti going down several hundred meters in coral material suggest such a secular deepening of the oceans, indicated by the contraction theory.

Lately HESS [1946] published a highly interesting paper in this connection. Many such truncated old volcanic cones have been detected during the War in the Pacific Ocean. They are called guyots and are found in depths ranging from about 950 to 1700 m. Less preserved forms appear in depths down to 3500 m. The higher ones rise 3000 to 4500 m above their surroundings. Supposing with Hess that the highest guyots are the youngest, dating immediately previous to the coral age these guyots would have a Precambrian age of 500 to 700 million years or three or four geocycles. Such as age would indicate a medium deepening of the ocean of 200 to 300 m in a geocycle.

Before knowing of the paper by Hess, I tried to figure out from various indications the secular deepening of the ocean demanded by the contraction theory. I will not present here a full discussion. The obtained estimate was about 100 to 150 m per geocycle. One possible explanation of the difference is an erroneous age estimate of the highest guyots mentioned by Hess. They may be older than suggested. Even accepting my more moderate estimate of oceanic deepening, we have hardly any other possible explanation for this phenomenon than a constant secular reduction of the oceanic basins.

With constant oceanic surface, a deepening of 100 to 150 m represents a water volume of 36 to 54 million km^3. Probably the Earth lost all its original atmosphere when the Moon separated. The present water is of magmatic origin, having escaped gradually as the crust formed and grew thicker and thicker. The solidification processes must have slowed down considerably with time and most of the present water formed in the earlier times. Making rather optimistic estimates for the possible water exhalation during the three geocycles since Cambrian times it seems difficult to admit a water production of more than a few million km^3 per geocycle. With a water content in the magma about five per cent, two million km^3 of water would require the solidification of more than ten million km^3 of magmatic rocks per geocycle. Obviously only a small fraction of the 36 to 54 million km^3 of water mentioned could come from such a source. In order to explain the deepening, we must admit a sensible additional reduction of the oceanic surface by folding and sedimentation.

Studying the interior structure of the continents we see hardly any signs of continental spreading but rather a surface reduction in the mountain belts. This orogenic surface reduction of the continents can produce an effective reduction of the ocean basins; that is, orogeny builds the continents up in height. They are truncated at the water level, spreading against the oceans by marginal sedimentation. Calculating with a medium depth of the ocean of 4.2 kms, a deepening of 100 to 500 m could be compensated by an oceanic surface reduction of 8.5 to 13 million km^2 per geocycle corresponding more or less to a radial contraction of the Earth of one per cent per geocycle. This estimate does not consider the secular sedimentation in the open ocean, the relative upbuilding of the continents indicated by the rise of the water level, the exhalation of new water and the salification by magmatic differentiation. As some of these additional factors partly compensate each other and as the data for a more detailed calculation are uncertain, we may be satisfied for the moment with the conclusion that the admission of a contraction of the Earth seems to be unavoidable, and that the rate of this contraction may be near to one per cent per geocycle of 165 to 180 million years.

The continents show an upworking of their basement by tectonic compression in all known spots. Sometimes tectonic forces have worked the ground more than once. As the actual surface of the continental blocks including the shelves is near to 180 million km^2 we may estimate that some 20 similiar upworkings may have been able to create the actual continents. Relying on the fact that the last 2000 million years show a more or less constant length of the geocycles, the total age of the continents and of the crust must lie somewhere between 3000 and 4000 million years. This estimate coincides exactly with newer estimates of the age of the Earth from radioactive data by Nier and HOLMES [1946].

Conclusions--Identical results in such discussions can only be expected in case of agreement regarding the physical conditions which have dominated the evolution of the Earth's crust. Nevertheless, the ideas of Vening Meinesz coincide in many respects with my own, sensible differences of appreciation are obviously caused by a difference of judging the fundamental causes. My conclusions favor the concept of a contraction of the Earth. Other factors as considered by Vening Meinesz, however, are also important. The mechanical theory of the regmatic shear pattern and the shaping of the continents is certainly not easy and simple, and complicated interactions must be considered. In the actual stage of development of the geomechanical science it is mainly important to define the fundamental notions with which we have to operate, such as elasticity and strength of the crust, possibilities for the elastic storage of forces, and the final estimate of the magnitude of forces involved. The discussion of the regmatic problems of geotectonics presents us with valuable indications regarding the intrinsic worth of certain theoretical concepts.

The contraction concept is not outmoded according to my conviction. On the contrary, as soon as we analyze the geotectonic problems carefully as mechanical problems, the contraction concepts seem to afford acceptable solutions of all the main problems of geomechanics. We must of course discard the old views and build up from the fundamentals of the mechanical theory. I must limit myself to this general statement because a more detailed discussion of the effects of a contraction of the Earth on the crust would lead too far and cannot be explained in a few words.

I cannot see how subcrustal currents could explain the problems as Vening Meinesz suggests. Many other authors have accepted the possibility of subcrustal currents [see, for example, GRIGGS, 1939]. Some critical remarks referring to the subcrustal current problem may be allowed. It seems improbable that subcrustal currents could create a polar drift. Such convectional currents must form a closed system and would show opposing directions beneath the crust. Thereby the total drift moment on the whole crust would probably become zero. The existence of subcrustal currents is extremely improbable as such. There is hardly any possibility for the formation of such currents without admitting a thermal cooling as final motor in some form. Radioactive research has made it clear that any sensible cooling of the Earth is impossible and that most of the thermal current leaving the Earth is produced within the crust itself. Any sensible convection at the depth of the asthenosphere is improbable for exactly the same reasons which oppose the explanation of the contraction of the Earth by thermal cooling.

There are many other difficult problems, when trying to analyze mechanically such a source of tectonic energy. With a low viscosity of the asthenosphere, the transfer of high stresses to the crust is impossible without assuming improbable velocitites for the currents. With high viscosity, the convection potential would become consumed mostly by internal friction. It seems that the substratum of the crust is layered and that the specific gravity of matter increases sensibly with depth. Such conditions must strictly oppose any convection. The asthenosphere must probably be considered as a passive weak layer beyond the solid crust. The only forces able to disturb the asthenospheric equilibrium will originate in the top layers in the form of a creep of the crust over the substratum or by disturbances of the isostatic balance, caused by the shift of weights within the crust or at the surface of the Earth.

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F. A. Vening Meinesz (Potgieterlaan 5, Amersfoort, The Netherlands, Author's closure)--It has been with a great deal of interest that the writer has read the discussion by Sonder. Leaving aside the question of nomenclature, which he is glad to leave to the public opinion among geologists and geophysicists, we differ in several basic viewpoints as, for example, the writer's conviction that the evidence indicates that convection-currents played an important part in the tectonic revolutions but does not think that the Earth's contraction could have been a major cause, while Sonder on the contrary does not believe in subcrustal currents and considers the contraction as primarily responsible for orogeny. Notwithstanding these fundamental differences in viewpoint, however, the writer thinks that as far as the sytematic shear pattern in the Earth's crust is concerned (which Sonder assumed so long ago), the opinions are not so far apart.

An important point the writer wants to make clear is that he does not at all want to suggest that the polar displacement is the only cause of shear having operated in the Earth's crust. This holds also with regard to the opposition his crustal shear hypothesis has met from UMBGROVE [see "References" at end of discussion, p. 108, 1946; p. 304, 1947]. On the contrary, it is his full conviction, that during its long history, the crust has been subject to a great many distorting forces which have profoundly affected its surface. In the first place of course we have the causes of the great tectonic revolutions but, in addition, other forces must have worked when crustal movements of other types have occurred. During most of these deformations, shear-stresses must have been present in the crust which no doubt have brought about many of the existing fault-planes in the crust. The areas where tectonic action has taken place are full of them.

My hypothesis, however, has another object. When stating a systematic shear pattern over the whole Earth's surface it is necessary to find an explanation of those fault-planes which belong to this pattern and this explanation must account for the systematic character. It has not been possibe to find many causes which could explain such a character; in fact he investigated only two possibilities, namely, a change of the Earth's flattening and a shift of the poles and the last was found to be remarkably appropriate for explaining a great many lines on the Earth's surface of a systematic character. It is important to add that one cause can directly bring about only two shear directions in each point of the Earth's surface. The many fault planes caused by other phenomena which show no system over the whole Earth's surface would in themselves have no systematic character unless they are influenced by the presence of the shear pattern mentioned. It is possible that this last effect has been a common occurrence; we may expect shear to follow the old zones of weakness unless they deviate too far. This means that there would be a preference for the old pattern as well as for a pattern of which the directions approximately bisect the angles of the old pattern. This last pattern would follow directions roughly in the N-S and E-W direction over great areas of the Earth's surface.

Returning to the main question, the writer's object has been to find an explanation of the systematic character which seems to be present in part of the fault planes and fault zones of the Earth's crust and it is a statistical question whether the solution given by the writer is likely to be the true explanation. If another solution can be found which shows a higher correlation, there is reason to prefer it above the one presented. As long as this is not the case, the present solution may be accepted as a possibility about which the future may gradually bring about a conclusion when new and more detailed evidence will allow a sharper statistical check. According to what has been said the presence of fault planes not coinciding with those of the net are no proof against it; their effect is to affect the statistical result.

The question about the cause which could have brought about the supposed polar shift is a second one, more or less independent of the main one. Contrary to Sonder, the writer believes undercurrents may well be responsible for it and he thinks that the computation given on page 23 of his paper gives some foundation to this view and shows that they can provide the required energy.

The writer avails himself of this opportunity of mentioning a discussion he had with Byleard after his return from Indonesia in which Bylaard gave as his opinion that a shear zone in thin plates must have a breadth comparable to its thickness. The consequence is that a shear zone in the Earth's crust may be expected to have a width of the order of some 30 km or more and so we may better understand the local irregularities we find in the major shear zones of the Earth's crust.

In these circumstances it seems still more doubtful whether we can speak of a tilt of the shear plane with regard to the normal to the crust, the discussion of which began on page 17 of the paper. As mentioned on page 39 there seems to be no evidence at the Earth's surface pointing to such a tilt.

Lastly it should be mentioned that there is an omission in Figure 10 on page 25 of the paper. As it was indicated under (8) on page 39 the major shear zone coinciding with part of the west coast of South America ought to continue in Figure 10 along the west coast of North America where the San Andreas fault forms part of it.

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DISCUSSION OF "EMPIRICAL AND THEORETICAL RELATIONS BETWEEN WIND, SEA, AND SWELL"

By H. U. SVERDRUP and W. H. MUNK

[Trans., v. 27, pp. 823-827, 1946]

Harold v. N. Flinch (Bucknell University, Lewisburg, Pennsylvania, April 30, 1947)--Sverdrup and Munk have contributed the first important post-war paper on surface waves. It is difficult to do justice to so comprehensive a piece of work in a short discussion, particularly since the theoretical analysis, on which a considerable portion of the paper is based, is still in press.

There is some doubt in the writer's mind as to whether the trochoidal wave form, generally recognized as the exact form of a surface wave, was used by the authors as a basis for the theoretical development of their equations and curves. The energy of the trochoidal wave can be expressed as

$$E = (w\pi C^6/2g^3)(\pi H/L)^2[2 - (\pi H/L)^2] \qquad \text{.................. (1)}$$

or

$$E = (wL^3/16\pi^2)(\pi H/L)^2[2 - (\pi H/L)^2] \qquad \text{.................. (2)}$$

where w is the unit weight of the water, and the wave velocity

$$C = \sqrt{gL/2\pi} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

as for the simple-harmonic gravity wave.

This is significant, since the energy determined by (1) and (2) can, within the range of the height-length ratio H/L, be considerably lower in value than the energy determined for a simple-harmonic wave of equal height and length, which energy can be found by dropping the second squared H/L term in (1) and (2). For the extreme form of the trochoid, the inverted cycloid, the trochoidal wave energy is just one-half as great as the corresponding simple-harmonic wave energy.

While the trochoidal form, being rotational, is not adaptable to the methods of classical hydrodynamics, it can be used fairly easily with the concept of energy transfer suggested by HELMHOLTZ [see "References" at end of discussion, 1890]. The writer applied this method to the trochoidal form in a study of the action of wind on waves, begun at the University of Minnesota in 1937, and [FLINSCH, 1946]. The experimental data obtained, while limited in range, are, in general, consistent with the results plotted by the authors, even to the scattering of data observed in Figure 1.

In the writer's analysis, the energy transfer was expressed in the form

$$k\rho' H(U - C)^2 dF = dE \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where k is a form drag coefficient, ρ' is the density of the air, F is the fetch, and U is the wind velocity. The well-known observations of STEVENSON [1874] and of CORNISH [1934] were combined to form a dimensionless parameter

$$(U/C^2)\sqrt{2gF}$$

The height-length ratio of well-developed waves (F more than 40 miles, U more than Beaufort 6) will then, according to these observations, be very nearly in direct proportion to the parameter.

On the basis of his experiments at the University of Minnesota, the writer determined the height-length ratio as, very nearly, proportional to the square of the parameter, for the initial conditions of wave development (maximum fetch, about 22 feet). With this relationship between height-length ratio, wind velocity, wave velocity, and fetch, the final solution of (4) was achieved, and the results plotted, with C/U as ordinate and the Froude parameter $\sqrt{2gF}/U$ as abscissa, much like the upper curve in the authors' Figure 2, except that a family of curves was plotted, each curve for a different height-length ratio, in place of the authors' single curve. Except for the shortest fetch (less than one foot), very little scattering was observed, and it was possible to predict, for a measured wind velocity and fetch, a theoretical value of wave velocity, height, or length that matched the corresponding measured value, well within the range of observational accuracy.

The writer suggests that this approach, rather than the expression of H/L as a single-valued function of C/U, will provide less scatter than is evident in Figure 1, at least for low values of C/U. The writer was unable to extend his method to the higher values of this velocity ratio, and is, therefore, looking forward with considerable interest to the publication of the authors' theoretical analysis.

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H. U. Sverdrup and W. H. Munk (Scripps Institution of Oceanography, La Jolla, California, June 16, 1947, Authors' closure)--Most of the interesting questions raised by Flinsch are answered in the theoretical discussion to which Flinsch refers, and which now has appeared in print. The theoretical paper is entitled; Wind, Sea, and Swell: Theory of Relations for Forecasting, by H. U. Sverdrup and W. H. Munk, U. S. Hydrographic Office Technical Report Number 1, Hydrographic Office Publication No. 601, March 1947.

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DISCUSSION OF "THE INFILTRATION APPROACH TO THE CALCULATION OF SURFACE RUNOFF"[1]

By HOWARD L. COOK

[Trans., v. 27, pp. 726-746, 1946]

W. B. Langbein (U. S. Geological Survey, Washington, D. C., October 2, 1946)--A paper on this subject has been long overdue. Cook's competent review of infiltration in relation to surface runoff should dispel much of the confusion and misinterpretation that has tended to retard progress in this field. The beginning was made by HOUK [see "References" at end of discussion, 1921], and lay dormant until Horton in 1934 and 1935, outlined the role of infiltration just at the time when renewed attention was being given to the effects of culture and land-use on runoff. Many ideas have been proposed since, some of which added greatly to the value of the physical approach and others, perhaps, were of profit only to the extent that they induced others to experiment with them. With this beginning now at an end, the juncture seems appropriate for just the kind of critical review Cook has made. Especially appealing to the writer is Cook's emphasis that infiltration is determinative of surface runoff only, and not total stream flow.

Like many others, the writer began his studies of the rainfall-runoff relation using Publication 101 by HORTON [1935] as a source book. Here indeed appeared a proper physical basis for tracing the generation of runoff from rainfall. Horton's hypothesis that the land surface was the sieve, separating runoff from soil-moisture and ground-water recharge appeared indeed attractive. Experience however has amply confirmed Cook's judgment that: (1) Infiltration data apply only to surface runoff (water which has not penetrated the ground surface since its precipitation). (2) Stream flow is composed of surface and subsurface components of varying volumes, generally indeterminable in ordinary stream-flow records. The hydrograph by itself gives no information as to the source of the flow. (3) Infiltration capacity figures apply only to specific type areas.

These circumstances more or less seem to force an analyst whose interest centers in stream flow as such, to adopt a different approach. The satisfactory nature of an infiltration index as applied to a basin complex suggests that empiricism can not be avoided. Hence, if empiricisms are necessary, it seems practical in problems of estimating runoff from rainfall to choose a path that leads more directly to an answer.

The simple rainfall-runoff correlation chart has, therefore, resumed a prominent place among hydrologic techniques. If applied to a definable period of time, such as a month or a storm unit of specified range in duration, then, there may be presumed to exist: (1) A statistical correlation between volume of rainfall and associated intensities; (2) as volume increases, greater areas contribute to runoff; and (3) there is no special need to define surface runoff as distinct from other phases of stream flow. We merely need to speak of direct runoff, that is, runoff directly associated with the causative storm, without inquiry into the course of the runoff.

Therefore, a simple chart which correlates volume of storm rainfall with associated runoff in terms of a suitable parameter that evaluates antecedent or initial condition cuts through the manifold details involved in application of the infiltration theory, and has in practice achieved a result that presents a challenge to that attractive and promising theory.

This conclusion on the other hand should not necessarily diminish the value of the infiltration theory in evaluation of the effects of different kinds of land use on stream flow.

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HOUK, I. E., Rainfall and runoff in the Miami Valley, Tech. Rept., pt. 8, Miami Conservancy District, 1921.

M. R. Lewis (Bureau of Reclamation, Boise, Idaho, October 28, 1945)--Cook has done well to bring out the confusion in definitions and basic concepts in this field. Particularly is this true of the clear presentation, in the introductory sections of the paper, of the distinction between surface and subsurface runoff.

The runoff from rainfall on most drainage basins will contain some subsurface water. As indicated by the author, when this subsurface water is derived from the zone of permanent or near-permanent ground water it can be reasonably well segregated on the hydrograph from surface flow. Perhaps the most important use of runoff estimates is in connection with flood flows, often, with maximum flood flows. During periods of intense floods the runoff from all but small drainage basins in areas of deep soil will include subsurface water. The writer has seen water infiltrate into the soil near the top of a slope while a few hundred feet below the crest it was returning to the surface and moving on down the slope as overland flow. Obviously, as the author points out, it is impossible to separate this type of subsurface flow from the surface flow by means of rainfall and runoff data alone. The runoff from a large basin may well include surface flow and subsurface flow ranging all the way from this type to perennial ground-water flow.

Nevertheless, the application of so-called infiltration indices derived solely from rainfall and runoff data on large and small drainage basins does appear to provide a more rational and altogether better approach to the study of flood flows than the mistakenly called "rational" method. Such indices will be greater than the true infiltration averages because they will include surface storage and less than these because they will exclude water infiltrated at higher levels but returned to the surface and included in runoff above the gaging stations. The author accepts the inclusion of surface storage but does not make it clear whether water infiltrated but returned to the surface is included or not in his definition of infiltration indices. As he says they might better be termed, "retention" indices.

The term, "coefficient," in the first paragraph of the section of the paper discussing infiltration indices, appears to be misused. The indices are used as subtractive terms and not as coefficients.

Howard L. Cook (U. S. Department of Agriculture, Washington, D. C., Author's closure)--The kind reception given the paper is sincerely appreciated. The author is particularly pleased with the general acceptance of the brief discourse on surface and subsurface runoff. Only a few short years ago such a statement would have aroused a storm of controversey. It is most encouraging to find that, in technical circles at least, there is no longer any question of the important contribution subsurface runoff can make to floods originating on areas of low subsurface storage capacity.

Koelzer points out that slope affects surface storage. The author regrets that he inadvertently omitted reference to this variable. The statement in question should have read: "For a given slope, cover and cultural treatment, surface storage is about the same for all soils, etc.".

Smith emphasizes that the infiltration characteristics of a soil vary with time. The author did not intentionally leave the impression that the soil is an inert mass. It is now quite generally understood that the properties of a soil, and particularly those that control infiltration, are never static but are in a continuous state of flux [SHERMAN and MUSGRAVE, 1942]. Perhaps failure to bring this out resulted from a too rigid compartmentalization of the field in the mind of the author and his effort to limit the subject matter to methods of calculation.

Smith also calls attention to a difficulty introduced by the variation of the time-intensity pattern of rainfall over a drainage area. This should be added to the list of problems demanding further study. It is understood, of course, that the problem is common to all methods of estimating runoff.

Langbein suggests a wider use of rainfall-runoff curves (often called P-Y curves). Curves that show the relation between "storm rainfall" and resulting flood runoff are particularly valuable. In addition to several primary uses, they constitute a valuable check upon runoff estimated by the use of infiltration data. But, as Langbein indicates, such curves cannot be used to evaluate the effect upon runoff of a change in soil, cover or condition. Here recourse must be had to the infiltration approach. It might also be pointed out that the latter is of considerable practical value in estimating the runoff that would occur under "extreme" flood-producing conditions; a value that cannot ordinarily be determined from P-Y curves.

It is most fortunate that Lewis caught the author's careless appelation of an infiltration index as a "coefficient." While the term has not infrequently been so misused, the practice should certainly not be perpetuated.

The many other points brought out in the discussions do not appear to require more than a grateful acknowledgment that they materially increase the value of the paper.

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SHERMAN, L. K., and MUSGRAVE, G. W., in Physics of the Earth - IX, Hydrology, Chapt. 7, pp. 244-258, 1942.

DISCUSSION OF "THE INFLUENCE OF TREATMENT AND SLOPE LENGTH ON RATE OF RUNOFF FROM COLLINGTON SANDY LOAM" by O. R. NEAL and C. C. BUTLER

[Trans., v. 27, pp. 837-842, 1946]

C. F. Izzard (Public Roads Administration, Washington, D. C., April 3, 1947)--The authors state that there was no consistent difference in the amount or maximum rate of runoff from the slope lengths of 70 and 210 feet. Considering only the check plots it will be observed that the maximum rate of runoff in inches per hour is consistently less for the longer plot although the differences are small in the storms of February 7, 1941, and May 30-31, 1940. For the other storms having larger differences in maximum rate of runoff the duration of the maximum intensity of rainfall is only one to four minutes, whereas in the February 7, 1941 storm the maximum intensity of rainfall lasted 11 minutes.

Theoretically the maximum intensity of runoff can be expected to be less on the longer plot unless the duration of the maximum intensity of rainfall is long enough to supply the greater depth of detention required for the longer plot. This theory holds for the storm of February 7, 1941, but appears to fall down for the storm of May 30-31, 1940, where the duration of the maximum intensity of rainfall was only two minutes. However, a possible explanation of this inconsistency is found in Table 9, which shows that the intensity of rainfall in the latter storm was in excess of one inch per hour for 26 minutes, suggesting that the maximum intensity of runoff was caused by sustained rainfall at a rate in excess of one inch per hour but less than the maximum intensity of 2.1 in/hr.

Consistent results as to maximum intensity of runoff in relation to length of plot can be expected with simulated rainfall at a constant intensity. In an actual storm, however, the rainfall intensity pattern, or order of succession of different intensities, and the duration of rainfall at each intensity, affects the results. For example, if the maximum intensity of rainfall occurs near the end of a storm when infiltration has been reduced to a low rate, and sustained rainfall at substantial intensities has provided a large amount of detention on the surface, the maximum intensity of runoff can be expected to be much greater than for the case where the maximum intensity of rainfall occurred near the beginning of the storm when the infiltration rate was high and very little detention had accumulated on the surface. For this reason, and there may be others, the data in Tables 2 to 6 cannot be expected to yield consistent results as to the value of C in the so-called "rational" equation.

Theoretically it does not appear that the length of the plot should affect the amount of runoff per unit area except that the longer plot might have less runoff per unit area because the increased length of time necessary to drain off the detention remaining after cessation of rainfall provides more opportunity for infiltration.

A suggested method of analysis of runoff rates, based on experience with simulated rainfall [see "Reference" at end of discussion, IZZARD, 1945], is to plot (on logarithmic cross section paper) depth of detention against rate of runoff at short increments of time throughout the entire period of runoff. These points will tend to line up during a period of constant supply. By extending a line drawn through such points to a rate of runoff equal to the rate of constant supply, the detention required for equilibrium runoff can be estimated. After equilibrium detention has been determined for several rates of supply, another line can be drawn through these points to derive an equation for equilibrium detention as a function of the supply rate for the given plot in the condition which existed during the storm from which the basic data were derived. Data from other storms may also be used provided the resistance to flow may be assumed roughly the same for all storms.

If satisfactory equations for detention at equilibrium can be derived for plots of several lengths, detention can be plotted against length for a fixed supply rate to determine the variation with length. According to laboratory data, detention should vary as the cube root of the length, provided the product of supply intensity in inches per hour and length in feet does not exceed 300 more or less. Beyond that limit [IZZARD, 1945] the type of flow changes from viscous to turbulent flow and a different detention-discharge relationship develops.

The method described has been used successfully in analysing runoff from an impervious surface, but it must be admitted that the problem is greatly complicated when dealing with previous surfaces. For the latter we can measure the rate of rainfall and the rate of runoff at any time, but so far no one has been able to measure continuously the rate of infiltration on a natural plot with natural rainfall. We can measure the total amount of infiltration. The problem then becomes one of distributing this infiltration over the period of rainfall and runoff so that the net supply rate and the amount of detention at any time can be estimated. The factors involved on pervious surfaces are so many that it becomes questionable as to whether mathematical analysis of overland flow data is worthwhile. From the research standpoint, however, understanding of the mechanics of this unsteady flow problem may serve to explain the lack of correlation so frequently found in studies of runoff data.

Reference

IZZARD, C. F., The surface profile of overland flow, Trans. Amer. Geophys. Union, v. 26, pp. 959-968, 1945.

O. R. Neal (Soil Conservation Service, New Brunswick, N. J., Author's closure)--Differences in maximum rate of runoff from slope lengths of 70 and 210 feet were consistent in direction but not in magnitude. The rate was higher in all cases from the 70 foot plot but the amount varied from 0.01 in/hr up to 0.78 in/hr. In the storm of July 8, 1941, when runoff rates were high, this difference was 0.42 in/hr. The design of conservation structures could be varied only slightly on the basis of differences of this magnitude.

Izzard points out the fact that many complications arise in dealing with runoff from pervious surfaces. Differences in the rate at which water enters the soil occur between cultural treatments and, for any given treatment, variations occur from the beginning to the end of the storm and between storms. Considering the storms of July 7, 1941 and July 8, 1941 the data in Tables 10 and 11 indicate that rainfall intensity was appreciably greater for the July 7 record. However, the percentage and maximum intensity of runoff from all treatments was greater for the July 8 record.

DISCUSSION OF "ASSIGNMENT OF FREQUENCIES TO A COMPLETELY ORDERED SET OF SAMPLE DATA" by BRADFORD F. KIMBALL

[Trans., v. 27, pp. 843-846, 1946]

E. J. Gumbel (Brooklyn College, Brooklyn, N. Y., June 10, 1947)--Probability coordinate papers are constructed in order to obtain straight lines for the observed frequencies which allow a simple forecast. Kimball's question, which frequency to assign to the m'th value, is important for the use of such papers designed for an unlimited variate since this frequency is the plotting position for the m'th observation.

In the writer's opinion, the following prerequisites must be made: (1) The plotting position must be such that all observations can be plotted. This condition is not fulfilled for the plotting positions m/n, and (m - 1)/n. They correspond to the original frequencies of the observations arranged in increasing or decreasing order of magnitude. Since the frequencies zero and unity cannot be plotted, these two procedures ignore either the largest or the smallest observation. (2) The return period of a value equal to or larger than, the largest observation, and the return period of a value equal to, or smaller than, the smallest observation should converge toward n, the number of observations. This condition is not fulfilled in Hazen's method since the choice of (m - 1/2)/n as plotting position leads to a return period 2n for the extreme observations. If n observations have led to a largest observation x_n, it seems hazardous to assume that this or a larger value should return, in the mean, in 2n observations. (3) The observations should be equally spaced on the frequency scale, that is, the difference between the plotting positions of the m + 1'st and the m'th observation should be a function of n only, and independent of m. This condition need not be fulfilled if the probabilities of the mean, median, or modal m'th values are chosen as plotting positions. Furthermore the choice of the mean and median m'th values need not fulfill condition (2). (4) The plotting position ought to be analytically simple, and have an intuitive meaning.

The writer has proposed to choose the probabilities of the most probable smallest and of the most probable largest value as plotting positions of the two extremes, and to determine the remaining n - 2 plotting positions from linear interpolation. Kimball proposes to choose the mean frequency of the m'th observation. As the characteristic value of the extremes, the writer chooses their modes whereas Kimball chooses a new kind of average. Kimball's procedure is simpler since it does not require any analytic calculations. If the sample is sufficiently large, both methods are practically identical since the differences are only of the order n^{-2}.

The test of fit on which Kimball is working is very interesting. The writer has calculated the expectation of the squared α difference of $G(x_m)$ from its expected value $m/(n + 1)$ which turns out to be $1/[6(n + 1)]$. If Kimball succeeds in finding the distribution of the squared difference, this test will henceforth rightly occupy the role which, up to now, is occupied, wrongly, by the Chi square test. Consequently the writer wants to encourage Kimball to continue this research.

B. F. Kimball (Port Washington, N. Y., Author's closure)--Gumbel's discussion has particular reference to the problem of plotting frequencies for the purpose of making a graphical fit to the observed sample data. From the point of view of equalizing errors in the frequency visually, (vertical errors, where frequency $F(x_i)$ is taken as ordinate and sample values, x_i as abscissa), his prerequisites (3) and (4) seem to be met, provided that scale of graph paper is such that vertical distance on the graph paper is proportional to $F(x_i)$. However, it does not seem to the writer that his prerequisite (3) is either necessary or desirable in all cases.

I should like to point out that in the use of the specially designed graph paper for fitting the distribution of maximum values to a sample of annual maximum flood flows, the ordinate is taken as proportional to the maximum flood flow x_i and the scale of the abscissa is taken such that the horizontal distance represents a linear function of x when the theoretical distribution of maximum values is satisfied (since graph paper is designed so that points of a theoretical distribution of maximum values will lie along a straight line). Hence for this type of graph paper, the discrepancies of sample points from theoretical curve (straight line) will be measured (either vertically or horizontally) by distances which are proportional to errors in x_i. Thus the visual balancing out of discrepancies of plotted sample points relative to a graphically fitted straight line involves the balancing out of discrepancies which are measured by distances proportional to variations of sample values x_i relative to their theoretical norms.

This type of fitting corresponds precisely to the second method of fitting discussed in my paper, page 845.

For the case of the distribution function of maximum values

$$F(x,\alpha,u) = \exp(-e^{-y})$$

$$y = \alpha(x - u)$$

let y_m denote the value of the reduced variable corresponding to the m'th ordered sample value, m = 1 being smallest and m = n being the largest. Thus

$$y_m = \alpha(x_m - u)$$

Take C as Euler's constant (C = 0.57722). Then it can be shown that

$$E(y_n) = C + \log_e n$$

$$E(y_{n-1}) - E(y_n) = -n\Delta \log_e (n - 1)$$

$$E(y_{n-2}) - E(y_{n-1}) = \binom{n}{2}\Delta^2 \log_e (n - 2)$$

. . . .

$$E(y_{n-r}) - E(y_{n-r+1}) = (-1)^r\binom{n}{r}\Delta^r \log_e (n - r)$$

For n = 10, denoting expected values $E(y_m)$ by $\bar{y}_m$, the results shown in Table 1 were found from the formulas given above. The figures in the last column give the values of the frequency $F(x_m)$ found from the formula

$$E[F(x_m)] = m/(n + 1)$$

Table 1--Values of functions

m	$\bar{y}_m$	$F(\bar{y}_m)$	$m/(n+1)$
1	- 0.990	0.0678	0.0909
2	- 0.584	0.1665	0.1818
3	- 0.284	0.2650	0.2727
4	- 0.012	0.3635	0.3636
5	0.257	0.4614	0.4545
6	0.544	0.5597	0.5455
7	0.868	0.6571	0.6364
8	1.267	0.7545	0.7273
9	1.826	0.8512	0.8182
10	2.880	0.9454	0.9091

which corresponds to the first method of fitting discussed in my paper. They are considerably different from the values used in the second method of fitting, especially near the extremes of the range. I find that for $n = 10$, Gumbel's modal frequencies at the extremes are $F(x_1) = 0.0655$, $F(x_{10}) = 0.9048$. It will be noted that the lower value 0.0655 is not very different from the value 0.0678 shown in the second column of the table, whereas the upper value 0.9048 differs considerably from the value 0.9454 shown in the table.

The dilemma which now presents itself is that the formulas given above for finding $E(y_m)$, when applied to large samples serve only to determine a few values of $E(y_m)$ near the upper extreme, until someone equipped with say 35 place log tables is willing to compute the complete triangle of differences of $\log_e m$ between $m = 1$ and $m = 100$, extending out to the 99th difference of $\log_e 1$. Perhaps such a computation would be a worthy task for the Mathematical Tables Project. If such a table of differences were available, it would be a comparatively simple task to set up a chart indicating values of $F(\bar{y}_m)$ for sample sizes up to 100. Until such a chart is available perhaps the best that can be done is to use the modal value at the lower extreme, and the values obtained from the above formulas as the two or three points at the upper extreme. A process of equalizing the differences in frequencies such as that suggested by GUMBEL [see "see Reference" at end of paper, 1945, eq. 30] can then be used to interpolate for the intervening frequencies.

Reference

GUMBEL, E. J., Simplified plotting of statistical observations, Trans. Amer. Geophys. Union, v. 26, pp. 69-82, 1945.

LETTER TO THE EDITOR

ACTIVITIES OF THE SUBCOMMITTEE ON HYDROLOGIC DATA OF THE FIARBC

The Federal Inter-Agency River Basin Committee (FIARBC) is composed of the Washington representatives of the five major agencies of the Federal Government interested in a sound and coordinated development of our river resources. The agencies include the Departments of War, Interior, Agriculture, and Commerce, and the Federal Power Commission. Under the aegis of the FIARBC, two comparable field committees have been organized, one for the Missouri River Basin, and the other for the Columbia River Basin.

The FIARBC naturally deals with a wide variety of activities having a major public interest. These include flood control, navigation, irrigation, power, water supply, recreation, and other uses. In order to cope with special technical or other problems as they arise from time to time, the FIARBC has created a number of subcommittees to advise upon subject matter in which the agencies have a community of interest or to recommend action to achieve a coordinated approach to a problem.

The first of these groups to be established was the Subcommittee on Hydrologic Data. It was established, as its name indicates, to look into various operational hydrologic subject matters. It in turn has had to set up working groups to look into particular specialized phases of applied hydrology. As the work of this unit has such far-reaching implications, the Inter-Agency Committee decided to have its work and activities brought to the attention of the American Geophysical Union. A general report on its activities may be presented to the Union at each Annual Meeting.

The Subcommittee on Hydrologic Data is composed not only of representatives from the agencies represented on the main Committee, but it includes also representatives of other Federal agencies that are concerned with hydrologic problems, including the Public Health Service and the Tennessee Valley Authority. Like the main Inter-Agency Committee, meetings of the Hydrologic Subcommittee are held monthly.

The first effort of the Subcommittee was directed towards compiling a set of maps showing the locations of stations at which precipitation and run-off data are secured. Maps of important drainage basins have been prepared, showing the stream drainage pattern on which has been entered the location of different types of precipitation gages, stream gages, snow courses, and reservoirs, at which all data are currently taken and compiled in public summaries. The information shown on the maps has been checked through the field offices of all the various Federal agencies as to locations, type of gage involved, and manner of operation. Efforts will be made to keep the maps current with periodic revision. They have recently been published cooperatively for use by the Federal agencies and their cooperators and will be available for reference in the principal field offices of the participating Federal agencies.

Another activity of the Hydrologic Subcommittee dealt with the possible use of automatic radio equipment. Knowledge of current precipitation and runoff at remote locations is often urgently needed for flood warnings and the operation of reservoirs. In order that the network of such radio transmitted data could be operated successfully area by area and without conflict in use, the Subcommittee worked out with the Federal Communication Commission the allocation of specific wave lengths for hydrologic use. These definite assignments also permit the manufacturers of radio-transmitting and receiving equipment to proceed with assurance in developing types of instruments suitable to such usage by the Federal agencies and their cooperators.

The Subcommittee has also endeavored to bring about integration among the Federal agencies engaged in snow research. One such study is currently under way in the Rocky Mountain area between the Bureau of Reclamation and the Forest Service. Another similar study is planned between the Corps of Engineers, the Weather Bureau, and the Forest Service in the Willamette Valley. Comparable studies are under way in the Sierras and in the Northern Rocky Mountains between the Corps of Engineers and the Weather Bureau. Analysis of the data is in progress by the two latter agencies at the Office of the Corps of Engineers in San Francisco.

The work of the Subcommittee has extended into other fields of activity. As some of these are highly technical and call for detailed study, a number of working groups have been established. One of these groups is engaged in the preparation of a glossary on snow terms for use by the Federal agencies involved in winter recreation. Another group is engaged in studying the need for extending the number of stations in order to obtain more information on the quality of water in streams used for irrigation. Two other problems have just been assigned for study by other units: One on the correlation of practices, terms, and type of measurements employed in the preparation of unit hydrographs; and the other is on investigation of the technique of measuring wave action on inland waterways.

E. N. MUNNS
Chairman, Subcommittee on Hydrologic Data
Federal Inter-Agency River Basin Committee
U. S. Forest Service, Washington 25, D. C.

REVIEWS, ABSTRACTS, AND BIBLIOGRAPHY

REVIEWS AND ABSTRACTS

MACELWANE, JAMES B., When the Earth quakes, Bruce Pub. Co., Milwaukee, 288 pp., 251 figures, bibliography, glossary, index, 1947.

This book, written primarily for the lay reader, is one which will long serve also as a reference work for professional seismologists. The author is recognized as an outstanding authority on seismology. His wide experience has made possible this most interesting discussion of earthquakes and their study.

Avoiding mathematical details and employing a style which commands continued interest and attention, the subject is treated in all its phases: Earthquake effects; descriptions of many large earthquakes which have occurred in various parts of the world since (and including) that of San Francisco in 1906; types of earthquakes; volcanic shocks; earthquake causes; possibilities of prediction; field studies of earthquakes; seismographs explained and types shown; what earthquake records tell us of earth structure; applications of seismometry to engineering, prospecting for oil and minerals, rock strains and rockbursts; microseisms and their use in tracking hurricanes at a distance.

The book closes with a discussion of rock faulting, an extensive appendix of references and notes; a glossary of geological and seismological terms and a full index. These, together with the lavish use of illustrations and diagrams, make the book readily understandable to anyone who wishes to have at hand an authentic, up-to-date, ready reference to all phases of earthquake study.

ERNEST A. HODGSON

BERLAGE, H. P., JR., Sunspot numbers and air-pressure deviations in the Netherlands Indies, K. Mag. Met. Obs., Batavia, Verhandelingen no. 31, 1947.

Among the more elusive problems in meteorology perhaps no two have commanded as much interest as the problems of periodicities and solar influences. Their solution, in addition to accounting for a major cause and explaining an important type of terrestrial variations, would also aid in projecting the general weather trend ahead.

Generally speaking these two problems have been attacked independently. Considering however, that changes in the Sun must exert a marked influence on the Earth's atmosphere and so disturb the periods current at the time, it seems far preferable whenever possible to attack these problems jointly. The reasonableness of this view is amply recognized in the paper under review. The result is that the year-to-year pressure variations in the general area of the East Indies which are closely related to the variations in the east monsoon rainfall in that area can to a great extent be interpreted in terms of solar changes and the three-year period in pressure reported in that region.

The general relationship which is assumed to exist between the Sun's spottedness and the pressure in that region is that the air column expands (lower pressure) during periods of more spots (hotter Sun) and contracts (higher pressure) during periods of few spots (cooler Sun). The existence of a substantial number of exceptions to this rule, though it does not invalidate the general relationship, leaves important gaps to be filled. Similarly, the attempt to explain the pressure variations in terms of a three-year period also fails of real success. Berlage's study goes a considerable way in resolving the two incomplete pictures into a single pattern. In the final analysis seven rules are formulated with the aid of which are deduced the series of high and low pressure years in the East Indies. As an example we quote Rules 1 and 2.

Rule 1--A high-pressure year follows one, two, and three years after a sunspot minimum year. It appears whenever the mean sunspot number of the year surpasses 20. It appears three years after the previous high-pressure year, if 20 has not yet been reached. When in the first case the mean sunspot number surpasses 50, the impulse will be called strong.

Rule 2--The next high-pressure year follows three, four, five, or six years later. It follows three years later if the mean sunspot number has not or not yet reached 81, or when the previous impulse was strong. It follows four, five, or six years later when the sunspot maximum has passed and the mean sunspot number has decreased below 81.

The important requirement for such a study, which is the availability of a long series of data for examination, has virtually been met. Pressure measurements at Batavia go back to 1866 and those at Bombay, whose annual values are closely correlated with the Batavia pressures, to 1847. Salt production records of Madura which "is, of course, a very sensitive indicator of drought and precipitation" extend the series to 1830.

Berlage was fortunate in choosing for his study conditions in the East Indies which are far less complicated than in other regions, especially outside the tropics. He comments on this and very correctly adds that "an attempt to pursue the influence of the long-periodic fluctuations of the atmosphere from the tropics into higher latitudes should not be discarded too soon."

IRVING I. SCHELL

KIRSCHMER, OTTO, and RIMKUS, KAZYS, Losses due to evaporation and melting of the alpine snow cover prior to spring thaw, Fiat. Rept. no. 1008, Office of Military Govt. for Germany (U. S.), Scientific Branch, Field Information Branch, Technical (U. S.), November 26, 1946

This report details a series of observations using a new method of measuring snow evaporation, which lead to the surprising result that snow evaporation in the mountains is essentially zero. Observation of snowfall and diminution of snow cover over a period of several years indicate that the gradual reduction of the snow cover during winter is not due to evaporation but to continual melting of the bottom layers, since even at air temperatures of - 30° C, the Earth under the snow cover shows temperatures slightly above 0° C. Consequently, the volume of mountain spring floods is not directly proportional to the total amount of winter snow fall.

WALTER B. LANGBEIN

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NOTES AND PERSONALIA

NOTES

Geophysicist wins Nobel Prize in Physics--Sir Edward Appleton of Cambridge University who did much to lay the ground work for radar has been named the recipient for the 1947 Nobel Prize in Physics for his contributions in exploring the ionosphere. He has been described as "one of the most outstanding scientists of our time in the field of Geophysics." At present, he is Director of the Department of Scientific and Industrial Research of Great Britain.

Call for word concerning manuscript translation of Russian papers on geology--The Committee on Russian Literature of the Geological Society of America has begun the compilation of a list of translations from Russian into English of geologic papers and books; that is, a list of translations extant in manuscript form in the United States. Please send information regarding such translations to the Geological Society of America, 419 West 119th Street, New York 27, N. Y. or to Ronald K. DeFord, Box 1814, Midland, Texas. The word geologic is used here in its widest sense.

If information about translations of recent publications is received soon enough, it will be included in forthcoming volumes of the *Bibliography and Index of Geology Exclusive of North America* and the *Bibliography of Economic Geology*, subject to permission from proprietors of translations.

Submarine gravity expeditions of the USS Conger--The USS *Conger*, Clark H. Fuller commanding, sailed from Balboa, Canal Zone, on August 23, 1947, on an expedition of five weeks for the measurement of gravity at sea, along the western coast of South America. The expedition was arranged with the cooperation of the Office of Naval Research, Navy Department, and Commander, Submarine Force, U. S. Atlantic Fleet. The Office of Naval Research also supported a portion of the scientific expenses, under a contract with Columbia University. Part of the scientific cost was supported by the Penrose Bequest of the Geological Society of America.

Paul C. Wuenschel made the scientific observations, with assistance from J. Lamar Worzel in the initial stages.

The gravity observations were made with a Vening Meinesz pendulum apparatus and a Bell Telephone Laboratories crystal chronometer loaned by the Woods Hole Oceanographic Institution. Additional observations of wave pressures were made with a sensitive pressure meter loaned by the Naval Ordnance Laboratory, to observe the relationship of wave motions to the disturbances of the pendulum apparatus. The purpose of these measurements was to investigate the gravity field in a region where the high Andes are adjacent to an ocean deep, and to extend gravity coverage of the Circum-Pacific earthquake belt.

A second expedition of the USS Conger left Balboa, Canal Zone, on October 19, 1947, on a nine-day expedition for the measurement of gravity at sea. On this occasion the measurements were made along the northern shore of South America, with the scientific observations made by Gordon R. Hamilton.

These observations continue the investigation of the strip of negative gravity anomolies which was found to parallel the Antillean arc in earlier measurements made in submarines of the United States and Netherlands navies.

This work is part of a two-year program of gravity observations at sea, sponsored by the Office of Naval Research. J. Lamar Worzel is in charge of the project, under the direction of Maurice Ewing of Columbia University.

Earthquakes, September and October, 1947--The United States Coast and Geodetic Survey has located provisional epicenters during this period as shown in Table 1.

Table 1--Provisional epicenters of the United States Coast and Geodetic Survey

Date	Time U. T.		Epicenter		Remarks
			Lat.	Long.	
1947	h	m	°	°	
Sept. 22	2	16.1	43.5 N	128 W	Off coast of Oregon
Sept. 23	13	53.1	41 N	125 W	Off Cape Mendocino, California
Sept. 26	16	02.3	26 N	126 E	Eastern Sea, off east coast of China
Oct. 3	8	11.0	16.5 N	99 W	Near southeast coast of State of Guerrero, Mexico
Oct. 3	23	32.2	19 N	102 W	State of Michoacan, Mexico
Oct. 5	18	41.0	3 S	140 E	Northern coast of New Guinea
Oct. 6	19	55.6	37 N	21 E	Near coast of southern Greece
Oct. 7	1	53.4	64.5 N	146 W	Central Alaska
Oct. 10	7	32.3	40 N	144 E	Off northeast coast of Honshu Island, Japan
Oct. 10	13	42.6	30 S	180	Kermadec Islands
Oct. 14	1	14.1	30 S	180	Kermadec Islands

The following shocks in Table 1 are tentatively listed as deep-focus types: September 26 (200 km), October 3 (100 km), and October 10, 7^h (300 km).

The epicenters listed were determined by the United States Coast and Geodetic Survey in cooperation with Science Service, the Jesuit Seismological Association, and a selected group of widely-scattered seismographic stations.

Philippine Fisheries Oceanographic Program--Two fishery and oceanographic investigation vessels have been fitted out by the United States Fish and Wildlife Service under the Philippine Rehabilitation Act of 1946, and have commenced operations out of Manila. They have been named Spencer F. Baird, after the first United States Commissioner of Fisheries, and Theodore N. Gill, after the American ichthyologist. The two ships were converted at San Francisco early in 1947 with the assistance of the United States Hydrographic Office. The Gill, with a 90 foot wooden hull, is the former Navy minesweeper Merit (AMc-90) and has a diesel engine. The Baird, a steel vessel, 143 feet long, is the former Army deep-sea tug LT-581, and has diesel-electric drive. Hugh W. Terhune is Administrator of the program, and Herbert E. Warfel is in charge of the scientific work.

Navy Antarctic Expedition--The icebreakers Edisto and Burton Island sailed from United States ports in November to revisit the Antarctic areas photographed by the 1947 "Highjump" expedition. Surveying parties of the Hydrographic Office will be landed by helicopter to make astronomical determinations of ground positions. E. T. Apfel of Syracuse University is geologist of the expedition.

New journal of the American Institute of Physics--A new monthly journal of the American Institute of Physics which is being designed to bridge the gap between technical journals and popular science magazines, will be published beginning early in 1948. David A. Katcher of the Naval Ordnance Laboratory has been named its editor.

Chicago Round Table broadcast on the weather--On October 26, 1947, the usual Sunday, University of Chicago Round Table discussion was devoted to the subject "What can we do about the weather?" Partaking in the Round Table were F. W. Reichelderfer, C. Warren Thornthwaite, Horace R. Byers, and Michael J. Ference, Jr. Copies of the broadcast may be secured for ten cents by writing University of Chicago Round Table, Chicago 37, Illinois.

Huancayo Magnetic Observatory transferred to Government of Peru--The Huancayo Magnetic Observatory, established by the Carnegie Institution of Washington in 1922, and maintained by that Institution since that time was transferred to the Government of Peru in June. John A. Fleming of the Carnegie Institution of Washington, who was instrumental in its establishment, J. M. Hydrick, and the American Cultural Attache to Peru, were the three representatives of the United States present for the ceremonies. The Observatory will function autonomously under a Directive Committee headed by Jorge Broggi, Director of the Geological Institute of Peru.

New observatory for measuring the radiation from the Sun--Daily determinations of the radiation of the Sun at sea level at Miami, Florida will be made at a new laboratory now being established by the Astrophysical Observatory of the Smithsonian Institution, L. B. Aldrich, Director. The new station will be able to study the effects of the more dense, more humid atmosphere than of the lower altitudes, as compared with observations made on mountain tops in California and Chile.

Centennial of Sheffield Scientific School--The celebration of the Centennial Year of Sheffield Scientific School of Yale University was held October 15 to 17, 1947, and consisted of a series of lectures and exhibitions, with a convocation on October 17. Joe Webb Peoples of Wesleyan University was the representative of the American Geophysical Union at the celebration.

Department of Meteorology and Climatology at University of Washington--In June 1947, the Board of Regents of the University of Washington established the Department of Meteorology and Climatology in the University. Phil E. Church has been named Acting Executive Officer and William L. Schallert has been appointed Instructor.

Publication of Geophysical Abstracts--The United States Geological Survey has resumed publication of Geophysical Abstracts after a four-year interval, during which they were issued by the United States Bureau of Mines. Geophysical Abstracts are published quarterly as an aid to those engaged in geophysical research and exploration. The bulletin covers world literature on geophysics contained in periodicals, books, and patents. It deals with exploration by gravitational, magnetic, seismic, electrical, radioactive, geothermal, and geochemical methods and with underlying geophysical theory and related subjects. Copies may be purchased singly or by annual subscription from the Superintendent of Documents, Government Printing Office, Washington 25, D. C.

Australian Antarctic Expedition--A five-year program of Antarctic research has been announced by the Australian Government. Under S. A. G. Campbell, Group Captain of the Royal Australian Air Force, LST 3501 is scheduled to leave Melbourne in mid-November for Heard Island, where two weather stations will be set up. Another weather party will be landed on Macquarie Island, and the Wyatt Earp will scout the Antarctic coast for further base sites, and make magnetic observations for locating the South Magnetic Pole.

Meeting of the International Meteorological Organization--The International Meteorological Organization held meetings in Ottawa, Canada during August and the fore part of September, and resumed their meetings in Washington during the last decade of September and the early part of October. Representatives from many countries were present. The Organization is made up officially of the directors of the meteorological services of the adhereing countries, aided by their scientific staffs. Twelve commissions have been established in the Organization to deal with the various scientific specialties.

Many of those attending the meetings, attended the New England Meeting of AGU, especially the sessions held jointly in Cambridge with the American Meteorological Society.

Visits from foreign geophysicists--During recent weeks, quite a number foreign geophysicists have visited Washington, some of whom have called at the office of AGU. Among the visitors have been Claudio Urrutia, Director, Observatorio Nacional, Guatemala City, Guatemala; Theresia Gudmundsson, Icelandic Meteorological Service, Reykjavik, Iceland; Eduardo Rohl, Director, Observatorio Cagigal, Caracas, Venezuela; S. K. Banerji, C. S. I. R. Laboratories, Delhi, India; M. B. Ramachandra Rao, Mysore Geological Department, Bangalore, South India; H. F. Frommurze, Government Geologist, Pretoria, South Africa; E. J. Ramirez, Director, Instituto Geofisico de los Andes Colombianos, Bogatá, Columbia; Z. Sekera of Czechoslovakia; J. Keranen and E. Palmen of Finland; J. Bessemoulin of France; Gustaf Slettenmark of Sweden; T. Hesselberg of Norway; H. Guttfeld of Palestine, N. P. Sellick of Rhodesia; W. Bleeker of the Netherlands; Po E of Burma;

Jean Lugeon of Switzerland; Otto Schneider of Argentina; S. W. Hsu of China; Nelson K. Johnson of the United Kingdom; Angel Rubio of Panama; and Luis E. Orduz; and Francisco Wismer R. of Columbia. Many of the above attended the meetings of the International Meteorological Organization held in Washington during September and October.

Schooner E. W. Scripps returns to peace-time service--The auxiliary schooner E. W. Scripps has returned to her peace-time duties as research vessel of the Scripps Institution of Oceanography. During the War she was operated by the Division of War Research, University of California, for experiments related to underwater sound and submarine warfare. As a result of her war service, the E. W. Scripps has a new main engine, enlarged laboratory space, and improved sonic sounding gear.

Service of Royal Research Ship Discovery II--The Royal Research Ship Discovery II is currently serving as a tender for Trinity House in the Thames Estuary, tending buoys and doing salvage work in connection with local shipwrecks.

The William Scoresby laid up for repairs--The William Scoresby after a tour of duty as a patrol vessel in the British Navy, operated from 1944 to 1946 with the Falkland Islands Dependencies Survey in the waters around Palmer Peninsula, was recently reported laid up in East India Docks in London.

PERSONALIA

Edwin D. Burchard, District Engineer of the U. S. Geological Survey in charge of surface-water investigations in North Carolina has recently retired. He has been succeeded by Edward B. Rice, member of the Survey staff for 18 years and until recently, District Engineer in Louisiana. William R. Eaton of the Survey staff in North Carolina has succeeded Rice in Louisiana.

Beno Gutenberg has recently been elected Foreign Member of the Accademia Nazionale Dei Lincei, Rome.

Thomas H. Johnson, now head of the Physics Section, Brookhaven National Laboratories, was recently awarded the Medal for Merit, the highest civilian award for war work, in recognition of his outstanding leadership in the development of his techniques for the measurement of blast and fragmentation effects of bombs, and the development of microwave techniques for measuring the velocities of projectiles. During the war, he was Chief of the Ballistic Measurements Laboratory and Associate Director of the Ballistics Research Laboratories at Aberdeen Proving Ground.

Warren A. Marrison of the Bell Telephone Laboratories has been given the Gold Medal of the British Horological Institute for 1947 in recognition of his research work in the development of the quartz crystal clock, which has become the world's most accurate chronometer.

Merle A. Tuve, Director of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has been named the recipient of the Research Corporation Award "in recognition of his exceptionally meritorious service in the advance of knowledge benefiting the people of this country in time of war and in peace. His pioneering in the use of the pulse-ranging technique to explore the ionosphere and in study of the proton-proton interaction to measure forces in the atomic nucleus contributed to man's knowledge of macrocosm and microcosm. By his outstanding technical leadership, perseverance, and enthusiasm he was primarily responsible for the development of a major improvement in ordnance which proved to be a determining factor in defensive anti-aircraft action and resulted in a material increase in effectiveness in offensive action against enemy air power. His interest and activity have been vital in fostering effective use of the results of physical science in biology."

Charles J. Vitaliano has accepted an appointment as Associate Professor of Field Geology at Indiana University. He was formerly with the Non-Metals Section of the U. S. Geological Survey.

Transactions, American Geophysical Union Volume 28, Number 6 December 1947

UNION, SECTION, AND COMMITTEE ACTIVITIES

The following committees have been established:

EXECUTIVE COMMITTEES OF THE UNION

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Time-Signal Service: Paul Sollenberger (Chairman); William D. George; Harlan T. Stetson

Cosmic-Terrestrial Relationships: Harlan T. Stetson (Chairman); Charles F. Brooks; J. Howard Dellinger; Jno. A. Fleming; Serge A. Korff; Donald H. Menzel; G. W. Pickard; John Q. Stewart; William T. Thom, Jr.

Award of the William Bowie Medal: L. O. Colbert (Chairman); Beno Gutenberg; Nicholas H. Heck; F. W. Reichelderfer; William E. Wrather

Surveys and Maps: G. Medina (Chairman); K. T. Adams; Helmuth Bay; Walter H. Bucher; Floyd W. Hough; Philip Kissam; Carroll F. Merriam; Joe W. Peoples; Herman J. Shea; L. G. Simmons; E. H. Vestine; George D. Whitmore; Ronald M. Wilson; Marshall S. Wright

Resolutions: Earl Ingerson (Chairman); John Putnam Marble; Charles F. Brooks

Affiliation with American Geological Institute: W. T. Thom, Jr. (Chairman); Ernst Cloos; O. E. Meinszer; F. W. Reichelderfer

REPRESENTATIVES

American Standards Association, Committee Z38 on Photography: Fred Anderegg

COMMITTEES OF THE SECTIONS

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Seismology

Executive Committee: Frank Neumann (Chairman); Perry Byerly; Beno Gutenberg; James B. Macelwane; Florence Robertson; V. C. Stechschulte

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Executive Committee: Horace R. Byers (Chairman); Benjamin Holzman; Woodrow C. Jacobs; F. W. Reichelderfer

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Executive Committee: Irwin Roman (Chairman); H. H. Howe; H. Freeborn Johnston; J. Wallace Joyce; D. G. Knapp

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Executive Committee: George F. McEwen (Chairman); R. H. Fleming; Waldo L. Schmitt; Edward H. Smith; H. U. Sverdrup

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Program Committee: Wilbur S. Burbank (Chairman); Eugene Callaghan; E. F. Osborn; Francis G. Wells; Howel Williams

Hydrology

Executive Committee: L. G. Straub (Chairman); Merrill Bernard; J. E. Church; W. G. Hoyt; W. B. Langbein; R. K. Linsley, Jr.; F. J. Veihmeyer; R. N. Wilson

Program Committee: R. N. Wilson (Chairman); membership is made up of the chairmen of all Permanent Research Committees indicated below

Permanent Research Committees (Hydrology)

(Note: Terms of appointment expire on June 30 of the year indicated.)

Chemistry of Natural Waters: L. V. Wilcox (Chairman); M. M. Ellis (1948); S. W. Lohman (1948); W. W. Aultman (1949); W. L. Lamar (1949); N. W. Rakestraw (1949); A. P. Black (1950); C. S. Howard (1950); C. S. Scofield (1950)

Dynamics of Streams: F. T. Mavis (Chairman); W. W. Rubey (1948); F. C. Scobey (1948); A. C. Trowbridge (1948); Hans Kramer (1949); W. C. Krumbein (1949); Gerard H. Matthes (1949); E. W. Lane (1950); Lorenz G. Straub (1950)

Evaporation and Transpiration: H. G. Wilm (Chairman); E. A. Colman (1948); A. Russell Croft 1948); C. W. Thornthwaite (1948); Marvin D. Hoover (1949); Joseph Kittredge (1949); H. J. Lutz (1949); Benjamin Holzman (1950); Luna Leopold (1950); Harold C. Troxell (1950)

Glaciers (Members and Cooperating Members, terms to be established): Francois E. Matthes (Chairman); C. Max Bauer; James E. Church; W. S. Cooper; James L. Dyson; W. O. Field, Jr.; Gerald FitzGerald; L. M. Gould; Weldon F. Heald; W. H. Hobbs; Arthur Johnson; Oliver Kehrlein; Lawrence Martin; Kenneth Phillips; Robert P. Sharp

Ground Water: S. W. Lohman (Chairman); H. F. Blaney (1948); Edward Burwell, Jr. (1948); G. W. Musgrave (1948); C. E. Jacob (1949); Roger Rhoades (1949); Nicholas A. Rose (1949); R. M. Leggette (1950); A. C. Swinnerton (1950); Chester K. Wentworth (1950)

Infiltration: G. W. Musgrave (Chairman); V. S. Aronovici (1948); Joel Fletcher (1948); W. O. Smith (1948); V. C. Fishel (1949); S. W. Jens (1949); M. R. Lewis (1950); H. S. Riesbol (1950); A. L. Sharp (1950)

Lakes (Terms to be established): Phil E. Church (Chairman); George Benton; J. L. Hough; C. S. Howard; G. E. Hutchinson; N. Allen Riley; R. R. Woolley

Land Erosion: W. C. Lowdermilk (Chairman); C. F. Stewart Sharpe (1948); Reed W. Bailey (1949); D. H. Eargle (1949); W. D. Ellison (1949); Carl B. Brown (1950); Kenneth Segerstrom (1950); Herbert C. Storey (1950)

Physics of Soil Moisture: L. A. Richards (Chairman); Willard Gardner (1948); F. J. Veihmeyer (1948); G. B. Bodman (1949); S. J. Richards (1949); Don Kirkham (1950); W. O. Smith (1950)

Precipitation: Merrill Bernard (Chairman); Glen N. Cox (1948); J. W. Howe (1948); R. W. Gay (1949); J. Otis Laws (1949); A. K. Showalter (1949); W. D. Ellison (1950); R. D. Fletcher (1950)

Runoff: Charles C. McDonald (Chairman); Bertram S. Barnes (1948); Edwin S. Cullings (1948); Charles R. Hursh (1948); W. C. Ackermann (1949); R. W. Davenport (1949); Gail Hathaway (1949); H. L. Cook (1950); Walter U. Garstka (1950); Walter T. Wilson (1950)

Snow: Richard C. Farrow (Chairman); Howard T. Barnes (1948); Joseph Kittredge (1948); Phil E. Church (1949); R. W. Gerdel (1949); R. F. Legget (1949); J. E. Church (1950); Ralph L. Parshall (1950); Robert A. Work (1950)

Special Research Committee (Hydrology)

Permeability: C. E. Jacob (Chairman); B. A. Bakhmeteff; M. F. Beecher; G. B. Bodman; W. A. Bruce; S. E. Buckley; F. T. Carson; J. M. DallaValle; Stanely M. Dore; R. B. Dow; Frank L. Duley; Ralph E. Fadum; George H. Fancher; Lyman Fourt; Marcus A. Hanna; Loranus P. Hatch; M. King Hubbert; O. W. Israelsen; C. F. Izzard; Norris Johnston; W. C. Krumbein; Oscar E. Meinzer; Morris Muskat; L. A. Richards; Sterling J. Richards; H. Ries; M. B. Russell; W. O. Smith

Tectonophysics

Executive Committee: M. King Hubbert (Chairman); Robert Balk; P. W. Bridgman; Wilbur S. Burbank; Ernst Cloos; James Gilluly

UNION ACTIVITIES

New England Meeting, September 17-19, 1947

In accordance with the announced plans, the Twenty-First Regional Meeting of the Union was held as the first New England Meeting on September 17 to 19, 1947. On September 17, the Meeting was held at Wesleyan University, Middletown, Connecticut, as a round table. At the morning session, the general theme was the review of methods and techniques applicable to the study of the structure and history of continents. At the afternoon session, the theme was the regional study of New England from the geophysical point of view.

On September 18, meetings were held both at Woods Hole Oceanographic Institution at Woods Hole, Massachusetts, and at the Institute of Geographical Exploration, Harvard University, Cambridge, Massachusetts. At Woods Hole, the sessions related especially to various aspects of oceanography, including gravimetric work at sea, and the tracking of hurricanes over ocean areas by microseisms.

The sessions at Cambridge on September 18 and 19 were held jointly with the American Meteorological Society, and bore especially on meteorology, terrestrial magnetism and electricity, and hydrology, and their interrelationships. These sessions were attended by quite a number of foreign meteorologists who stopped on their journey from Ottawa to Washington where sessions of the International Meteorological Organization were held.

The General Chairman of the Meeting was Richard M. Field. Working with him on the Committee were Charles F. Brooks, H. G. Houghton, C. O'D. Iselin, H. B. Kinnison, Joe Webb Peoples, and Harlan T. Stetson. A further account of this Meeting, as well as many of the papers, will appear in subsequent issues of the Transactions.

SECTION ACTIVITIES

SECTION OF HYDROLOGY

Minutes of the Sixth Meeting of Washington Group--Twenty-four members and guests of the Washington Group Section of Hydrology gathered for a supper meeting in the South Building of the U. S. Department of Agriculture on November 12, 1947, to hear Gerard H. Matthes discuss the subject, "Preservation of our Rivers." Serious dangers of stream channel deterioration, in some cases obliteration, face the Nation as a result of accelerating activities in flood control, power and other forms of surface water control or utilization. Dams and other structures offering obstacles to channel flow may adversely affect the regimen of streams by reducing their ability to transport the natural sediment load, thereby causing excessive aggradation above the structures and degradation, and aggradation downstream. The damaging after effects, usually unforeseen at the time of construction, may have greater consequences than the problems the channel works were designed to solve. These need to be given the most careful consideration in river development plans. Numerous examples were cited to illustrate these dangers. The meeting adjourned at $21^{h}00^{m}$ following a period of questions and lively discussion.

Bernard Frank, Secretary

COMMITTEE ACTIVITIES

American Standards Association, Committee on Photography, Z38--Fred Anderegg, representative of AGU on this Committee, advises that a meeting of this Committee was held on November 13, 1947 to discuss: Nomenclature and symbols; processing and processing equipment; photographic characteristics of illuminants; exposing equipment; supports for sensitive coatings; sensitivity to radiant energy; physical dimensions of sensitive materials. Members having suggestions bearing on these matters should communicate with Fred Anderegg, Department of Geology, Princeton, N. J. Please send copies of communications to the office of the Union as well. He further reports that two standards recently have been approved by the American Standards Association. Number Z38.2.1-1947, dated July 15, 1947, is the "American Standard Method for Determining Photographic Speed and Exposure Index." This describes a sensitometric method of determining and expressing the photographic speed of roll films, film packs, miniature camera film, sheet film, and plates. Number Z38.7.16-1947, dated July 17, 1947, is the "American Standard Method for Determining Resolving Power of Lenses for Projectors for 35 mm Slidefilm and 2 × 2 Inch Slides."

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ADDITIONS TO THE MEMBERSHIP OF THE AMERICAN GEOPHYSICAL UNION, SEPTEMBER 11 TO OCTOBER 20, 1947

Adkins, Dr. John N., 186 Beacon St., Boston, Mass. (bd)
Alcock, Dr. E. D., 3412 Caruth St., Dallas 5, Tex. (b)
Allen, Mr. Charles T., 2914 Vista Street, N. E., Washington 18, D. C. (a)
Allen, Dr. John Eliot, Dept. of Earth Sciences, State College, Pa. (bf)
Allen, Mr. L. D., Apartado 246, Caracas, Venezuela (abd)
Alvarez, Mr. Manuel, Jr., Nogal No. 52, Mexico, D. F., Mexico (h)
Ambrose, Dr. John W., Queens University, Kingston, Ontario, Canada (abcdefgh)
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Andrews, Dr. E. H. A., 2908 W. 83 St., Inglewood, Calif. (abh)
Armstrong, Dr. H. S., Dept. of Geology, McMaster University, Hamilton, Canada (efgh)
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Bajza, Mr. Chas. C., P. O. Box 40, Casper, Wyo. (e)
Baker, Mr. Glenn J., 909 Giddens-Lane Bldg., Shreveport 4, La. (dh)
Baker, Mr. James W., Virginiatown, Ontario, Canada (df)
Balay, Señor Mariano A., Malabia 2445, Buenos Aires, Argentina (e)
Barksdale, Mr. G. L., c/o C. P. C., Maracaibo, Venezuela (ab)
Barnes, Miss Mary E., 808 S. Fifth St., Champaign, Ill. (abcdefgh)
Barnett, Mr. D. G., Geological Dept., Union Producing Co., Beeville, Tex. (abdh)
Barton, Mr. Jackson M., 402 Schweiter Bldg., Wichita 2, Kans. (bdh)
Baugh, Mr. M. H., 1529 Roosevelt Ave., Falls Church, Va. (h)
Baum, Mr. Robert, Seismograph Service Corp., P. O. Box 1590, Tulsa, Okla. (b)
Bay, Mr. Helmuth, 1104 National Press Bldg., Washington 4, D. C. (a)
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Beckner, Col. Lucien, 1204 S. Second St., Louisville, Ky. (abefh)
Beckwith, Mr. Irving E., 902 Selden Road, Iron River, Mich. (dh)
Beedle, Mr. Edward W., Jr., Gulf Refining Co., Mattoon, Ill. (cg)
Beiser, Mr. W. S., P. O. Box 1463, Savannah, Ga. (g)
Bell, Mr. Gordon L., Dept. of Geology, University of Utah, Salt Lake City, Utah (fgh)
Bellamy, Mr. John C., 5617 Drexel Blvd., Chicago, Ill. (c)
Benish, Mr. Richard H., 4123 Marlowe St., Houston 5, Tex.
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Berry, Dr. Charles T., University of Connecticut, Ft. Trumbull Branch, New London, Conn. (bef)
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Boling, Mr. Kenneth G., 367 State St., West Branch, Mich. (ab)
Booth, Mr. Robert T., Standard Oil Co. of Texas, P. O. Box 1249, Houston 1, Tex. (bd)
Bosco, Mr. Francis N., 853 Elm St., Denver, Colo. (b)
Boucher, Mr. F. G., 3611 S. Utica St., Tulsa, Okla. (bd)
Boutakoff, Dr. N. A., Kern Trinidad Oilfields, P. O. Box 55, San Fernando, Trinidad, B.W.I. (eh)
Boyle, Mr. James P., Jr., 607 N. E. 15th St., Oklahoma City, Okla. (d)
Brady, Mr. L. F., Museum of Northern Arizona, Flagstaff, Ariz. (fg)
Brantley, Mr. J. E., 600 Continental Bldg., Dallas, Tex. (ab)
Brenner, Mr. Morris, 3855 Rodman St., N. W., Washington 16, D. C. (abcdefgh)
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Brockway, Mr. Levalley I., 506 Lancaster Bldg., Calgary, Alberta, Canada (abd)

Broman, Mr. Isidore J., 35 E. 15th St., Austin, Tex. (bcdf)
Brons, Dr. H. H., Seismograph Service Ltd., 3A London Wall Buildings, London, E. C. 2, England (bd)
Brown, Mr. Henry W., P. O. Box 801, Tulsa 2, Okla. (b)
Brown, Mr. Vergil N., 540 Commerce Exchange Bldg., Oklahoma City, Okla. (ab)
Brown, Dr. W. L., 350 Bay St., Suite 602, Toronto, Ont., Canada (d)
Bryan, Mr. Frank, Nelson, Okla. (bg)
Buhle, Mr. Merlyn B., Illinois State Geological Survey, Urbana, Ill. (dg)
Bunn, Mr. John R., 325 W. Fourth St., Tyler, Tex. (h)
Bunton, Mr. Paul B., 2900 Connecticut Ave., N. W., Washington 8, D. C. (abcdefgh)
Caldwell, Mr. Loren T., 580 Normal Road, De Kalb, Ill. (abcdefgh)
Cheney, Mr. Leroy A., Scripps Institution of Oceanography, La Jolla, Calif. (e)
Chew, Mr. R. S., 820 Mills Bldg., San Francisco 4, Calif. (b)
Chittenden, Mr. M. C., 703 Esplanade, Redondo Beach, Calif. (b)
Compton, Mr. Milton E., Jr., 3149 Mt. Pleasant St., N. W., Washington 10, D. C. (ad)
Congdon, Mr. Clyde G., The Texas Co., Rangely, Colo. (abcdefgh)
Cornwall, Dr. Henry R., 1 Second St., Calumet, Mich. (fh)
Cowles, Col. Hubert N., Hqtrs. Hawama, Hickam Fld., T. H., APO 953, San Francisco, Calif. (ac)
Cox, Mr. Richard H., Eleele, Kauai, T. H. (g)
Critchfield, Mr. Howard J., State College of Washington, Dept. of Geography, Pullman, Wash. (abcdefgh)
Dahlberg, Mr. Jack K., P. O. Box 61B, Broken Hill, N.S.W., Australia (b)
Daley, Mr. A. Cowles, 1191 N. Los Robles St., Pasadena 6, Calif. (abfh)
Davis, Prof. Harmer E., 301 Engineering Materials Lab., University of California, Berkeley, Calif. (bg)
Davis, Mr. William W., 2165 E. 26th Pl., Tulsa, Okla. (abcdegh)
Derrick, Mr. Clarence J., 2021 Kenilworth Ave., Los Angeles 26, Calif. (b)
De Woody, Mr. D. A., P. O. Box 2038, Pittsburgh 30, Pa. (b)
Donn, Mr. William L., 523 Kingston Ave., Brooklyn 25, N. Y. (ceg)
Dortch, Mr. W. R., Socony-Vacuum Oil Company, Apartado Aereo 4034, Apartado Nacional 1140, Bogota, Colombia (b)
Dunaway, Mr. James H., 258 Humble Bldg., Houston 2, Tex. (bc)
Dunlop, Mr. Arthur C., 2810 Ashby Ave., Berkeley 5, Calif. (abcdefgh)
Dyson, Dr. James L., Geology Dept., Lafayette College, Easton, Pa. (g)
England, Mr. C. M., University Station, Enid, Okla. (bd)
Enslin, Dr. J. F., Geological Survey, P. O. Box 401, Pretoria, South Africa (ad)
Espenshade, Prof. Edw. B., Jr., Dept. of Geography, Northwestern University, Evanston, Ill. (ac)
Everitt, Mr. Jas., P. O. Box 101, Sidney, Ill. (be)
Eyestone, Mr. Willis B., 2740 S. Troy St., Arlington, Va. (cg)
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SPECIAL ANNOUNCEMENTS

Regional Meeting in California, February 13 and 14, 1948--The Twenty-Second Regional Meeting of the American Geophysical Union is to be held at Berkeley, California, February 13 and 14, 1948. Originally this meeting was to be one of the Section of Hydrology alone, with F. J.

Veihmeyer, Chairman of the South Pacific Regional Committee of the Section of Hydrology, in charge of general arrangements. As we go to press, word has just arrived that the plan to extend the scope of the meeting to include other sections, is developing, and Dr. George F. McEwen, Scripps Institution of Oceanography, La Jolla, California, has been named General Chairman to cooperate with and to coordinate the representatives of the various sections, which will act as the General Committee. Representatives of the Sections have been designated as follows: Geodesy, Comdr. R. D. Horne (1426 Post Office and Court House, Los Angeles 12, California); Seismology, Prof. Perry Byerly (University of California, Berkeley, California); Meteorology, Mr. Woodrow C. Jacobs (Scripps Institution of Oceanography, La Jolla, California); Terrestrial Magnetism and Electricity, Dr. J. Jay Jakosky (International Geophysics, Inc., 1063 Gayley Ave., Los Angeles 24, California); Oceanography, Capt. O. W. Swainson (114 Custom House, San Francisco, California); Volcanology, Prof. Howel Williams (University of California, Berkeley, California); Hydrology, Prof. F. J. Veihmeyer (University of California, Davis, California). Dr. Beno Gutenberg (California Institute of Technology, Pasadena, California) and Dr. Walter C. Lowdermilk (1620 Le Roy Avenue, Berkeley 9, California) have also been appointed members of the General Committee. Prof. J. W. Johnson (University of California, Berkeley, California) has been designated Chairman of the Committee in Charge of Local Arrangements. Persons interested in attending or taking part in this meeting should get into touch promptly with one of those above, sending copies of correspondence to Prof. Johnson.

Twenty-Ninth Annual Meeting, Washinton, D. C., April 21 to 23, 1948--The Twenty-Ninth Annual Meeting of the American Geophysical Union will be held in Washington, D. C., April 21 to 23 (Wednesday through Friday), 1948. Sessions will be arranged to extend over three (or perhaps four) full days. Please note that the program dates are about one week earlier than for the Annual Meeting in 1947.

This first announcement of the meeting is also an invitation to communicate plans for papers. Titles and abstracts should be sent in as soon as possible, and not later than February 20, 1948. They may be sent to the office of AGU at 1530 P Street, N. W., Washington 5, D. C., or to the secretary of the appropriate section, as follows:

Geodesy	Frank L. Culley	4716 Huron Ave., S. E., Washington 20, D. C.
Seismology	Florence Robertson	4349 Forest Park Blvd., St. Louis 8, Missouri
Meteorology	Woodrow C. Jacobs	4111 W St., N. W. Washington 7, D. C.
Terrestrial Magnetism and Electricity	David G. Knapp	3827 W Street, S. E., Washington 20, D. C.
Oceanography	Richard H. Fleming	Division of Oceanography, Hydrographic Office, Navy Dept., Washington 25, D. C.
Volcanology	Francis G. Wells	U. S. Geological Survey, Washinton 25, D. C.
Hydrology	Ray K. Linsley, Jr. or	5517 Glenwwod Road, Bethesda, Maryland
	Ralph N. Wilson (Program Chairman)	3900 Hamilton St., Apt. L302 Hyattsville, Maryland
Tectonophysics	Wilbur S. Burbank	3346 Runnymede Place, N. W., Washington 15, D. C.

The Chairman of the Committee on Meetings (J. P. Marble, U. S. National Museum, Washington 25, D. C.) invites suggestions and comments that will be helpful in planning the proposed meeting. Especially invited are comments relating to papers and symposia bearing on more than one section. Complete manuscripts of papers should be forwarded in triplicate by the end of March 1948, in order that news releases may be prepared. In transmitting papers and abstracts, advice should be given on time (most papers are allowed from 10 to 20 minutes) and projection equipment required. If papers are written in collaboration, please indicate by whom they will be presented. Arrangements can be made for presentation of papers by authors who are unable to attend the meetings. Papers for publication only are also welcome for consideration for the Transactions.

John Putnam Marble, Chairman,
Committee on Meetings

General Assembly of the International Union of Geodesy and Geophysics, August 19 to 28, 1948--Once more attention is called to the General Assembly of IUGG to be held in Oslo, Norway, August 19 to 28, 1948 (see Announcement in October 1947 issue, page 822).